Solar energy potential in Montana

SOLAR ENERGY POTENTIAL IN MONTANA
(Report to the Environmental Quality Council)

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prologue

What follows is the result of a little over a year's study of solar energy and what it can do, I have made no attempt to be unbiased in advocacy of solar energy as a preferred power source; the facts speak for themselves. After having looked at the various methods that are employed or could be employed to generate power, I'm convinced and I hope to convince you that solar energy is superior to fossil fuels and nuclear fuels when all factors are considered. The fact that in some instances solar energy is somewhat more expensive than energy now produced will ameliorate itself as the costs of fossil fuels rise (as inevitably they must) and as the dangers of nuclear power become more apparent. Thus, for those who share concern for the quality of life and for the fact that there is only one earth to live with, hopefully this paper will present convincing evidence that extensive development of the sun's energy must begin now.

The following makes no serious attempt to extensively develop the physics of solar energy or the technologies by which it is utilized. Only the barest and most easily comprehensible account of it is presented since I suspect that most readers will not care to study solar energy in detail. But for those that care to, there is an extensive bibliography in which a good part of this information is represented.

For some of the calculations I've done, there are also several appendices sketching the procedure I followed.

Hopefully an interest in using solar energy will be stimulated or, at the very least, awareness of the ecological problems inherent in development of Montana's coal fields. At any rate, there are myriad ways to put the sun to work--many of them are quite simple and inexpensive. All of them can be ecologically sound. If anyone does incur an interest and has questions that this paper doesn't answer feel free to contact me for further information.

advantages of solar energy

Why should anyone want to use the sun for anything but growing plants and making winter disappear? Even though it has been conclusively shown that sunlight can be converted into forms of energy which are easily itilizable for space heating, cooking, electricity production and other things, currently existing methods of energy production employing coal, oil or nuclear fuel are prevalent and, at least at the present time, they are cheaper and more widely available. Is there any reason for extensive development of a new source of energy?

Answers to these questions are becoming more apparent as the prices of current conventional fuels increase and as supplies of them dwindle. Already shortages due to diminishing non-renewable fuel resources and exacerbated by ever increasing demand for energy are being felt in many parts of the United States and other industrialized nations. No matter what federal energy officials and power company executives promise about their future availability, it is obvious that allieviation of the short supply can only be temporary. Clairvoyance isn't necessary to see that the earth has only limited supplies of coal, oil, gas and even nuclear fuels and that eventually these must be exhausted no matter how conservatively they are used. Power company advertisements, which will have you believe that the solution to an energy crisis lies in the development of Montana coal field or North

slope oil reserves are blatantly specious. At best, this solution is transient—at worst, an ecological disaster.

Nor can the solution to energy or resource shortages be found in recycling or conservation. These, of course, will postpone the time when our resources are finally exhausted, but they cannot stave off that time forever. Thus, as has been tersely shown in books such as The Limits to Growth, any continuing exploitation of non-renewable resources must inevitably result in depletion of that resource. Furthermore, by our dependence on these resources for the accouterment of this consumer culture, their depletion means change, if not disaster for our civilization.[1]

What to do then? Certainly conservation will extend the easy availability of energy resources. Conservation should not be taken to mean simply curtailment of some of the more wasteful expenditures of energy, but also curtailment of all frivolous demands which anyone could well do without. No one really needs an electric toothbrush, an electric garage door opener, two televisions or an electric can opener. Similarly, trail bikes, snow mobiles and the like can by and large be done without. Disposable aluminum drink containers, at the price

[1]See The Limits to Growth, reference 10 in the general bibliography

of .3175 kwhr a piece in energy alone,[2] are most certainly a frivolous demand on resources. But ultimately conservation must mean immediate and drastic curtailment of the growth of energy demands, for if demand for energy (an other natural resources) continues at its present growth rate, our resources will be exhausted much sooner than with no growth at all. A graphic illustration is provided by our use of coal. If the present supply of coal will last for 400 years[3] at the current rate of use, then given only a 2% annual rate of growth for demand, this supply shrinks to enough for only 10 years.[4] A pointed argument for zero resource-demand growth. Supplies of natural gas and oil shrink simi-

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[2]Aluminum reduced from bauxite by electrolysis at 100% efficiency which is never the case, requires about 1.93 x 10^4 kwhr of electricity per metric ton. (Chalmers, Energy). Take an average aluminum beverage container to weigh 20 grams; then it takes .3858 kwhr to make only the aluminum for one can. That doesn't include the other energy costs of making it. At the industrial rate for electricity charged by Montana Power of about 1¢ per kwhr that's .3858¢ per can. Similarly, for steel cans, weighing an average of 55 grams a piece, it would take .0314 kwhr to make the steel for one can assuming the energy to cost 1¢ per kwhr and 100% efficiency (27.5 calories per mole of iron). If a vending machine holds an average of 100 aluminum cans, that's 38.58¢ of metal in each soft drink vending machine for every 1000 people in the US, that's $81,018 of aluminum cans in vending machines alone. At a turnover of 100 cans every month, that's $972,216 or 972,216 kwhr of aluminum cans in one year from these disgruntling machines. How much of this is re-cycled?

[3]The actual figure for coal reserves is irrelevant here although 400 years is one estimate of these reserves. The point I want to make is how the growth rate of the demand affects the availability of coal.

[4]R.T. Robiscoe, "The Effect of Growth Rate on Conservation of a Resource", American Journal of Physics, IV: 5 (May 1973), p. 719. The 2% growth rate of demand is a conservative figure - 5% or 7% would be closer.

larly, but since known reserves are much less in this case, their future availability is also much shorter.

Beyond conservation, new sources of energy must be found and developed if energy is to continue being consumed at present rates or even higher rates. Nuclear power will of course supply part of the needed power, but to my mind it is not a very elegant way of doing it if the possible environmental consequences are considered. Certainly coal, oil and gas will continue to partially meet the demand for energy until they become too scarce and expensive, but again the argument for uncontrolled exploitation of these fuels is not convincing. Let me elaborate.

In the case of fossil fuels, a short trip to Los Angeles is quite enough to convince yourself that increased use of these fuels in Montana will not make the big sky any prettier. Just how onerous the problem will be is difficult for a Montanan used to relatively clean air to imagine. In neighboring North Dakota lignite-fired generating plants along the Missouri River dump a plume of waste gas into the air visible for over 30 miles. And these plants are smaller than those planned for Colstrip. The Four Corners generating complex pours out enough atmospheric pollutants daily to qualify it for the rather dubious distinction of being the one of the world's largest polluters.[5]

[5]It poured out, at the beginning of its operation, 300 tons of particulate matter per day into the atmosphere. See Holdren and Herrera, Energy.

The complex is about the same size as the one planned for Colstrip and like the Colstrip plants, supplies power to cities remote from it--Los Angeles, Phoenix, Las Vegas among them.

Most of the coal for these western generating complexes will come from strip mining, one of the largest imaginable disruptions of the earth's surface. In fact only about 10% of the nation's coal reserves are amenable to strip mining. A similar percentage of Montana's coal is available for strip mining[6], a proposition that will ultimately disturb about 1000 square miles of eastern Montana.[7] To develop the remaining 90% of the coal reserves deep mining techniques must be used. Nation-wide it is estimated that 71,000 square miles of land will be strip mined at an environmental cost that cannot be calculated.[8] An area of land equal in size to West Virginia and Pennsylvania and yet only 10% of the coal reserves will have been tapped. Certainly a profligate use of land.

Going beyond environmental damage, which is not a very convincing argument to those removed from its immediate consequences, let's see

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[6]Don Schwennesen, "Montana Faces a Vast Strip Mining Boom", Environmental Pollution in Montana, ed. Robert Bigart (Missoula, MT, 1972), p. 180.

[7]Ibid., p. 182.

[8]"Feds Eye Regulations for Strippers", Environmental Science and Technology, VI: (January, 1972), p. 27.

what the depletion of fossil fuels means industrially. It is obvious that the ease of transportion by car will cease as will other means of transport that cannot be converted to a non-fossil fuel. Furthermore, plastics and many synthetic fabrics will become very expensive since they use petrochemicals as one of their principle ingredients. The scarcity may be mitigated by a decrease in the quantity of plastic garbage offered to consumers, but it will certainly make for inconveniences, too. Count the articles of clothing that are made with synthetic fabrics. Perhaps it would be best to postpone the day of scarcity by developing another energy source which does not use fossil fuels.

Nuclear generating plants can be expected to produce a large share of future energy needs, but it, too, is not a blessing without mitigation. Technical problems with both reactors and radioactive waste disposal remain to be solved. Recently, an issue of controversy has been the safety of reactors. Whether or not all possibilities of a catastrophic breakdown of an operating reactor have been eliminated is a moot point-one that has not yet been resolved and certainly ought to be before nuclear reactor construction proceeds full-tilt. The dimensions of an atomic calamity are too great to be slighted, as the danger to life and environment is not only immense but long-lived.

The problem of radioactive waste disposal hasn't been satisfactorily solved either. The Atomic Energy Commission feels that underground

chance of surviving the next two weeks.[13]

Of course that's an extremely unlikely situation. But it does illustrate the magnitude of the problem. These wastes are extremely hazardous to all biological organisms, especially the more complex ones, such as people. And the hazard is not a short lived one either. The wastes will remain dangerous for 500 - 1000 years. The fuels for breeder reactors are even more odius. Should they manage to escape safe confinement, the time they remain dangerous, if not sufficiently diluted, must be measured in thousands of years rather than hundreds.

Nor is any particular confidence merited in the storage facilities for these wastes. In fact the storage tanks at the reactor in Hanford, Washington, have already developed leaks. Ten of the 149 tanks there have already leaked, seeping 200,000 gallons of radioactive waste into the ground.[14] The remaining "sound" tanks must not develop leaks for at least 500 years if the dangers from these wastes is to be eliminated. This is not a very confidence-inspiring record so far.

Using a fusion process to produce energy is the saviour by which some hoped to be delivered from an energy crisis. If the process can be harnesses, it certainly could make energy in a virtually unlimited supply. But to date a fusion process has been sustained for only a very small part of one second. The problems involved in generating

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[13]R.T. Robiscoe deserves credit for this calculation.

[14]John Holdren and Phillip Herrera, Energy. (San Francisco, 1971), p. 80.

underground disposal in bedded salt is the safest method[9] but a recent attempt to use an underground salt mine at Lyons, Kansas, resulted in opposition from the Kansas citizens who would have to live with a radioactive garbage dump in their midst, an indication that all was not safe with the method of disposal. An indication of the magnitude of the wastedisposal problem is the amount of radioactive waste accumulated. It is estimated by the AEC that there will be roughly 400,000 megawatts of installed generating capacity by 1985.[10] By 1995 another estimate has the figure at about 600,000 megawatts.[11] (Actually these estimates should probably be reduced somewhat since installation of nuclear plants is lagging behind schedule.) Considering the amount of radioactive waste a nuclear plant usually produces, there will be about 600 billion curies of stored radioactive waste.[12] Furthermore, if the world's population is 6 billion there will be 100 curies of radioactive wastes (consisting principally of strontium - 90 and cesium -137) per person. If each person where to take his 100 curies and sit in front of it for a couple of minutes, he would have about an even

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[9] John O. Blomeke, Jere P. Nichols and William C. McClain, "Managing Radioactive Wastes", Physics Today, XXVI: 8 (August, 1973), p. 36-42.

[10] Donella H. Meadows, et al. The Limits to Growth. (New York, 1972) p. 81.

[11] Chauncey Starr, "Energy and Power", Energy and Power. Edited by the Scientific American (San Francisco, 1971), p. 3-15.

[12] Meadows, p. 81.

temperatures of 50 million degrees centigrade and containing the matter heated to that temperature are immense, and they certainly won't be solved quickly. Assuming that they are solved however, the problems created by waste heat from fusion power plants could be difficult enough by themselves. This problem of global heat balance is inherent in almost any type of energy production, but when unlimited energy becomes available, then so will unlimited thermal pollutions.

By now the point I want to make about solar energy should be obvious. It can meet our energy demands but without the problems of limited fuel supply or pollution inherent to fossil-fueled or nuclear generating plants. In fact sunlight falling on the earth has 31,000 times more energy than is presently consumed and the winds contain 100 times more energy.[15] The fuel supply is eternal and virtually pollution-free. If the 1000 square miles of Montana that are to be decimated by strip mining were covered with solar collectors instead and the energy converted to electricity at an over-all efficiency of 30% after the Meinels[16] scheme, then kwhr of electricity could be produced in an average year.[17] If the same scheme were to be used on a national scale, then one million megawatts of electrical power could be derived from about 5000 square miles of land in the southwest-

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[15] Lawrence Rocks and Richard P. Runyon, The Energy Crisis, (New York 1972), p. 60.

[16] See A.B. Meinel and M.P. Meinel, "Physics Looks at Solar Energy", Physics Today, XXV: 2 (February, 1972).

[17] This estimate is based on actual insolation data for Great Falls over the period 1952 - 1967. See Appendix 1.

ern United States. This is 50% of the present total energy consumption of the United States, and roughly 20% of the projected total energy deman for the year 2000. Compare the 5000 square miles that would be used for solar energy with 71,000 square miles of land that will be disturbed by strip mining. It is clearly a more efficient use of land. Also the sun will shine on these 5000 square miles long after the 71,000 square miles have been stripped, and furthermore the earth's surface remains intact thereby producing no disturbance to water tables or problems with reclamation. As a bonus, solar energy will not disrupt the global heat balance as all other methods of energy production necessarily do.

There must be a catch somewhere or solar energy would long since have been our major source of energy. The economics of solar energy are at present unfavorable. While the fuel is forever free, the equip= ment to convert solar energy in its raw state is not and therein lies the costs. All utilization of solar energy is capital intensive, that is, large capital expenditures are required initially but thereafter the cost of producing energy is limited to maintenance costs alone. In the following pages I hope to convince you that solar energy is indeed practical both economically and technically and will become even more so as the prices of conventional fuels rise.

It is reassuring to know that a source of energy exists that has none of the ecological problems associated with conventional or nuclear fuels. But since sunlight is obviously quite dilute, falling on the earth at a maximum rate of 1.5 calories per cm^2 per minute,[1] means must be found to collect this energy or to concentrate and collect it. As I shall show in a later chapter, most uses of thermal energy for power production require temperatures much higher than those that unconcentrated sunlight can produce if they are to be at all efficient. Even applications for which lower temperatures are suitable, such as space heating, must utilize some apparatus to collect sunlight. This is the shortcoming to easy utilization of solar energy. But before I sketch some ways by which this is done, a few things about the nature of the sun and sunlight ought to be discussed.

The intensity of solar radiation is usually measured in langleys, defined so that one langley equals one calorie/cm^2-min. If at some place in Montana solar radiation fell on the earth at an average of 350 langleys per day, then 200 m^2 receives 2.56 x 10" calories or 1.02×10^9 BTU of energy per year. In fact, 350 langleys/day is about the average insolation rate for Montana and 200 m^2 is about the size of the roof of a small house. Thus the roof of a small house receives

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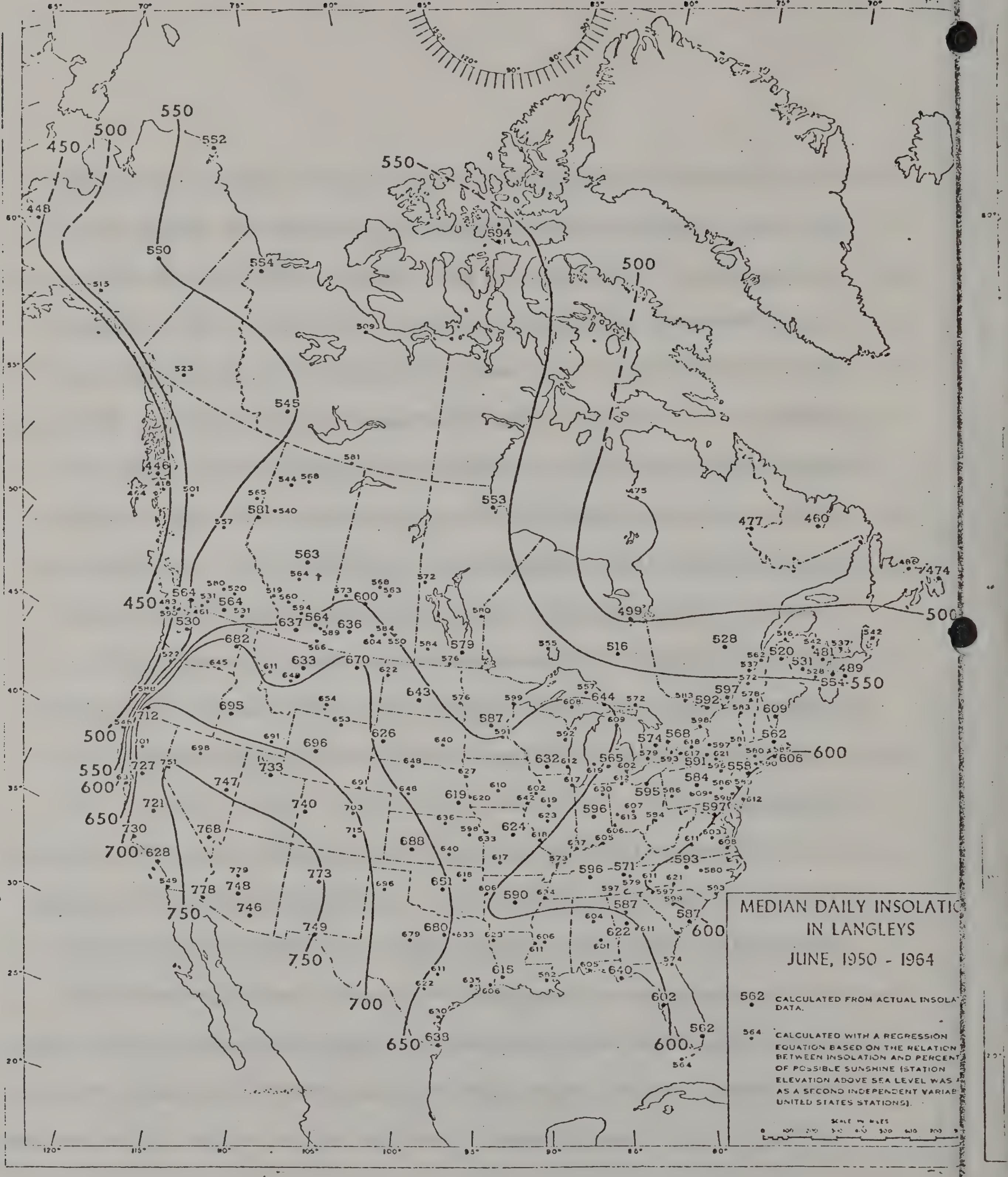
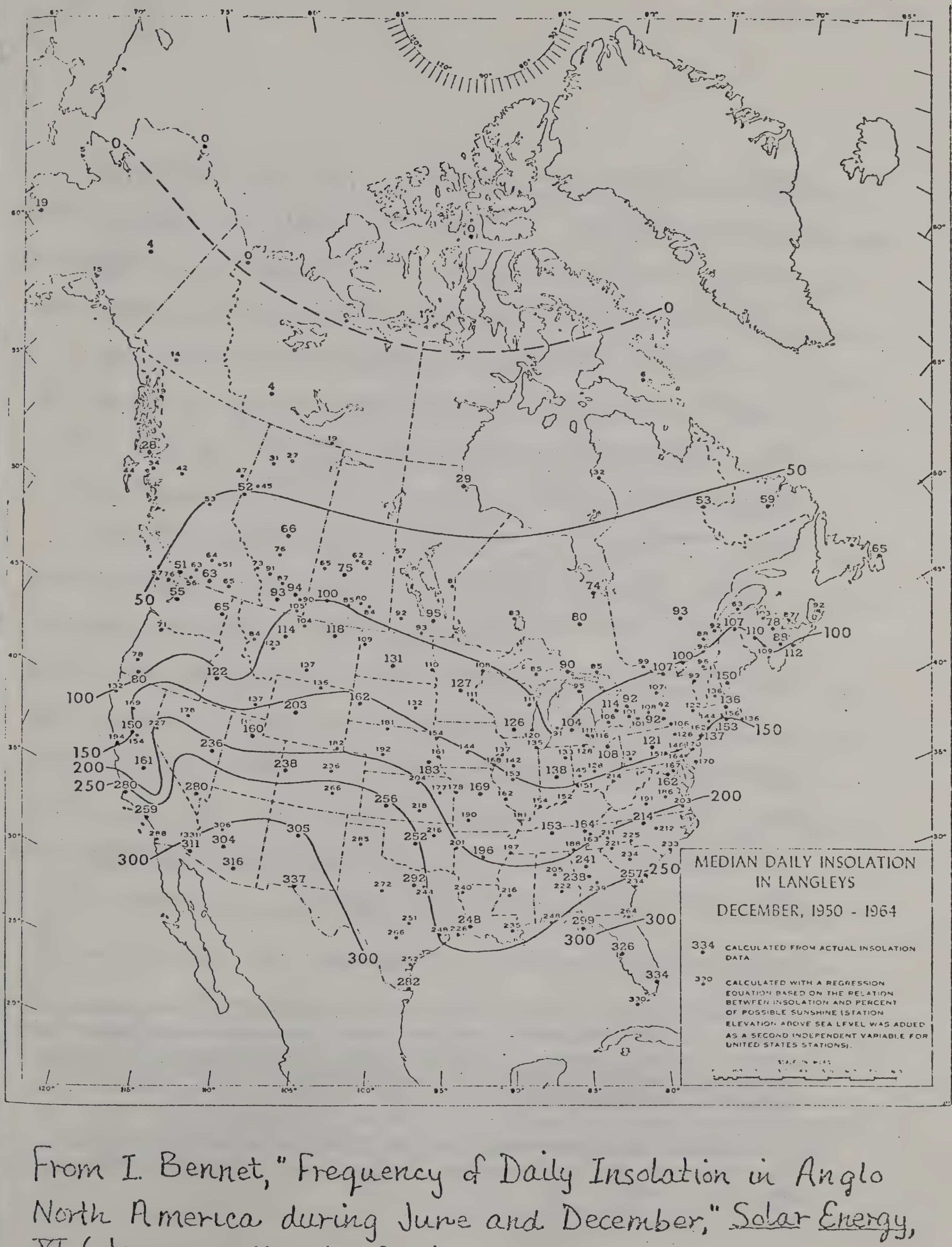
[1]1.0 cal/min cm^2 = 3.69 BTU/ft^2 min = .0698 watts/cm^2.



From I. Bennett, "Frequency of Daily Insolation in Anglo North America during June and December," Solar Energy, XI (January-March, 1967).



From I. Bennet, "Frequency of Daily Insolation in Anglo North America during June and December," Solar Energy, XI (January-March, 1967).

roughly 5 times more solar energy on its roof than is needed to heat it for an average year.[2] However, the insolation rate does not remain constant throughout the year, but varies from a low of 114 langleys/day in December to a high of 633 langleys/day in July (see figures 1 and 2).[3] During the winter, when the heating load is greatest, the insolation rate is least. But even during January, when the heating loads are most severe, the solar energy from 200 m^2 is about 1-1/2 times more than is needed to heat a 15,000 BTU/DD house. It thus appears reasonable to use sunlight for space-heating in Montana.

Solar radiation received at the earth's outer atmosphere amounts to nearly 2.0 cal/cm^2 min, but after traveling through the atmosphere, it is reduced in rate to anywhere from 1.5 cal/cm^2 min to practically nil. This dissipation is accounted for by absorption and scattering of the light by the constituent molecules and particles of the atmosphere. The amount of depletion from the initial value of 2.0 cal/cm^2 min depends on the length of the sun's path through the atmosphere and also on the density of particulates in the air, on the density of

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[2]These numbers are calculated using 15,000 BTU/degree day as the heating load for the house, and the normal annual heating degree days given in Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1941-70 (see reference 4). The 200 m^2 is assumed to be horizontal.

[3]Bennett, I., "Frequency of Daily Insolation in Anglo North America during June and December," Solar Energy, XI (January-March, 1967), pp. 51-52.

pollutants such as sulfur or nitrogen compounds, and on atmospheric humidity. All other factors being equal, the amount of depletion from the initial value of the solar constant is directly proportional to the optical path length. Thus, higher altitudes receive more sunlight, and winters are less sunny than summers. But the optical path length is not the only factor that reduces insolation rates in the winter.

The solar constant, or the intensity and rate of solar insolation, also depends on the angle at which sunlight strikes a surface. In winter this angle deviates most from normal incidence, consequently, the intensity of sunlight is not so great as during the summer when the angle is closest to 90°. (See figure 3.)

Cloud cover affects the sun's intensity in a familiar way, either diffusing the light so that sunlight does not follow a direct path to earth or blocking it out almost entirely. As we shall later see, clouds affect the collection of sunlight in an important way, but they don't make it completely impossible.

For completeness' sake there is one last factor affecting the solar constant for a specific place. The earth does not orbit the

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[4]These figures represent mean daily insolation on a horizontal surface and are based on actual data for Great Falls. The degree days are also actual data for Great Falls. Also see Monthly Normals of Temperature, Precipitation, and Heating and Cooling Degree Days 1941-70.)

sun in a perfect circle, but the orbit has an eccentricity of .017 from which the ratio of apihelion to perihelion distance from sun to earth can be found. The difference in distance affects insolation rates within a range of 3.3%.[5]

There is an interesting postscript on the effect of atmospheric pollutants on the solar constant. A recent study showed that in Houston, Texas, the solar constant has decreased 23% in the last half century, and in Washington, D.C., it has decreased by 16%.[6] These decreases are attributed directly to the effects of increases in atmospheric pollution. Given time enough and no abatement of pollution rates, using sunpower in smog-filled cities may well prove impractical if not impossible.

Solar radiation can be divided into two components: direct beam and diffuse radiation. Direct beam radiation, that coming directly from the sun, comprises the largest portion of solar radiation on a clear day—90% or more depending on atmospheric conditions. Diffuse radiation is that which has been scattered and reflected by the atmosphere, ground cover or clouds. It is most intense near the sun but is by no means limited to its vicinity. On cloudy days when the

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[5] Farrington Daniels, Direct Use of the Sun's Energy (New York, 1974), p. 15.

[6] R. K. Swartman, C. Swaminathan, and J. G. Robertson, "Effects of Changes in the Atmosphere on Solar Insolation," Solar Radiation, XIV (January, 1973), pp. 197-202.

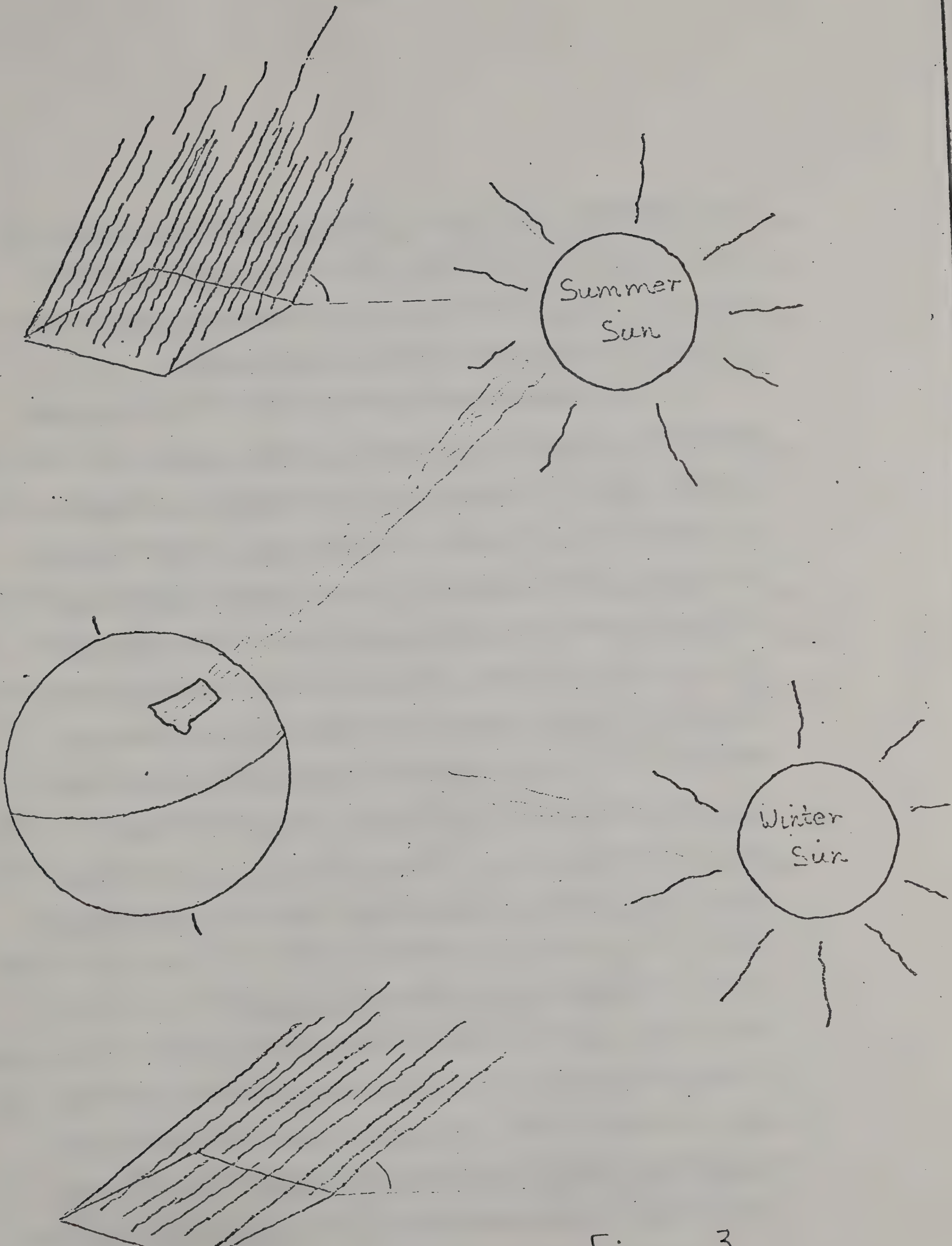

Figure 3

sun is obscured, it is the only radiation reaching the earth. The sum of direct beam and diffuse radiation gives total hemispheric radiation. Later the importance of distinguishing between these two components of solar radiation will become apparent.

The most commonly measured value of solar radiation is total hemispheric radiation on a horizontal surface recorded either hourly or daily using an instrument called a pyranometer. The Weather Bureau has data for total hemispheric radiation on a horizontal surface recorded for various places and varying lengths of time, the stations in Montana being at Great Falls and Glasgow. Only at Great Falls are these data taken at hourly intervals—Glasgow records only total daily insolation. One problem with these data is their inaccuracy—estimated to be ±5% for accurately calibrated instruments and ±10% for those less carefully calibrated. A second problem with insolation data is the lack of it. In Montana only the two cities mentioned keep any sort of a record of insolation and only one of these keeps an hourly record. Later the importance of hourly radiation and weather data for estimating the performance of solar heating systems will become clear. Right now suffice it to say that the lack of data makes it very difficult to predict a solar energy system's performance for areas of Montana at which the climatic conditions are very much different than those at Great Falls or Glasgow. There have been studies done by various people to correlate and predict insolation

rates by using other weather data. In general all that can be said about these predictors is that they are not so accurate as the not so carefully calibrated pyranometers (i.e., their accuracy is about $\pm 10\%$) but if other data is lacking, these predictors are all that remain.

Direct beam radiation, measured by a pyrheliometer, is measured at even fewer stations in the United States and none of them in Montana. The instrumentation required to measure this component is somewhat more complex as it requires that the pyrheliometer be continuously oriented in the direction of the sun. In fact it is always very important to know where the sun is relative to either a pyrheliometer or pyranometer so that the direction of the direct beam radiation can be calculated. (See appendix I.)

There is at least one more thing of interest about the sun. The sun is, to a good approximation, a perfect black-body. That means that its irradiance at a specific wavelength is given by

$$c\rho(\lambda)\,d\lambda = \frac{8\pi hc^2}{\lambda^5}\,\frac{1}{e^{hc/\lambda Tk} - 1}\,d\lambda.$$ [7]

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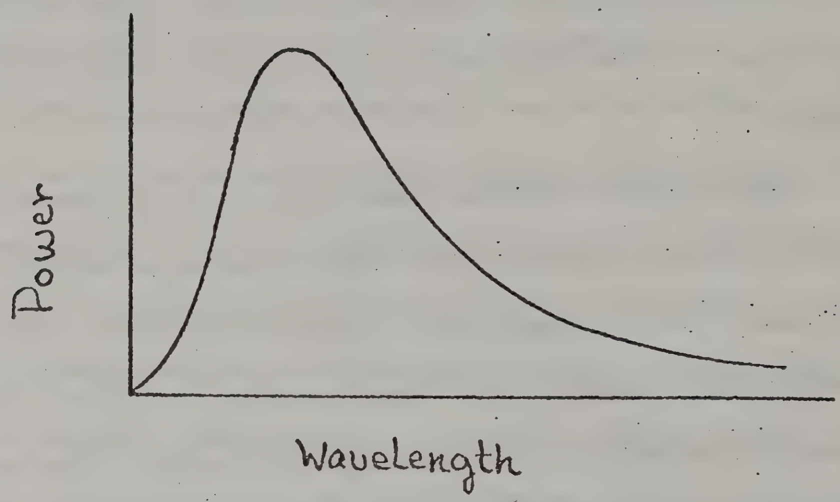
[7]This equation was first derived by Planck. Irradiance has units watts/cm^2. The other parameters in the equation are: λ = wavelength, h = 6.63×10^{-27} ergs sec, e = 3×10^{10}cm/sec, k = 1.38×10^{-6} ergs/deg.

When the power is graphed versus wavelength, we get a figure that looks like this:



Actually any blackbody, or near blackbody, will have an irradiance versus wavelength curve like this. In fact any body that is above absolute zero in temperature radiates some energy to its surroundings (and vice-versa). Just what the intensity-wavelength curve is depends on the temperature T of the body. Later, when selective surfaces are discussed, I'll talk about this again. But now, let's see what some of the equipment does that converts sunlight to useable energy.

using solar energy

Historically, the sun has been put to many uses. Generating electricity, distilling water, heating houses, cooking, metallurgy—all these and others are possible applications of solar energy utilizing no other fuel but the free stuff from the sun. Not all of these are useful in Montana, however. All of the methods for utilizing solar energy could be used but not all of them are economically practical. In fact, without more excuse than economics and convenience, water distillation, cooking and metallurgy will be dismissed from further consideration here. Anyone who would like to know something about the manner in which the sun can provide energy for these processes can consult the literature on solar energy.

There are two general applications of solar energy: high temperature and low temperature. High temperatures are needed for the economic operation of such things as steam electric generating plants, while low temperatures can be used for space heating and other employments where the efficiency of the equipment involved is not dependent on temperature or where its efficiency, if temperature dependent, is of little concern.

Why the concern for efficiency if the fuel is free? Because while the fuel is free, the apparatus for collecting and using it is not. Thus, if there is a device which we wish to power by solar energy that has an overall efficiency of 10% (including the efficiency of the collecting apparatus) and another machine with an overall efficiency of 20% that is also solar-powered, then the second device uses one half as much area of collectors as the first for the same total energy output. Translated into dollars, this means that the collecting apparatus for the first device costs twice as much as that for the second, and as a consequence, the energy from it is more expensive per kilowatt hour.

How is the efficiency of a solar energy using device determined? Except for photovoltaic conversion (solar cells), almost all methods of converting solar energy into mechanical or electrical energy involve heat engines. The efficiency of a heat engine is a function of the temperature at which it operates, the maximum efficiency, ν, being determined by the laws of thermodynamics. In terms of absolute temperature[1] of the fluid entering the heat engine, T_i, and the absolute temperature of the exhaust fluid, T_e, the maximum efficiency is

[1]Absolute temperature is temperature in degrees Kelvin, or equivalently, the algebraic difference between temperature in degrees Centigrade and absolute zero which is -273°C.

$$\nu = \frac{T_i - T_e}{T_i}.$$

So to make ν as great as possible, T_i must be made as large as possible and T_e as small as possible.

In some cases it is conceivable that the overall efficiency of a machine is of no great concern. These cases are almost invariably for machines which consume or produce no great amount of energy, that is, small-scale applications or for machines where both the fuel and equipment to use it is cheap. But for large power plants the capital invested in the equipment to utilize any sort of fuel is by no means a trivial sum. So the temperature of the fluid used to turn the turbine (or whatever the machine may be) must be as high as possible. Let's see what this means for our solar energy using device (hereinafter referred to as a SEUD).

Imagine that the solar constant for some place is 1 cal/cm^2 min. Furthermore, suppose that the overall efficiency of our SEUD is 40%, and that we want to produce energy at the rate of 1000 kilowatts. Then we need about 3.58 m^2 of collector to produce 1 kilowatt or 3580 m^2 for 1000 kilowatts. At an overall efficiency of 5%, the area of collectors we need to produce energy at the same rate is octupled or is about 28,640 m^2. Now if we want to produce energy at the same cost, then the collectors and the additional land they

occupy used in the 5% efficient device must cost less by a factor of 8 assuming the other equipment to be of equal cost—not necessarily true. Obviously, this is a situation that we would like to avoid.

Now then, what temperatures, T_i and T_e, do SEUD's of 40% and 5% efficiency require? Assuming that the working fluid is water, the temperature T_e must be at the least 100°C (212°F) if a steam turbine is used. Then T_i for the 40% efficient device is about 350°C and for the 5% SEUD it is about 120°C, a difference of 230°C! Clearly, high temperatures are necessary for a high efficiency heat engine.

What kind of collectors can be used to produce high temperatures and what sort produce low temperatures? Basically there are two collector types: focusing and flat-plate. Focusing collectors take the solar radiation falling on a large area of land and concentrate or focus it into a small area with resultant high temperatures; temperatures as high as 3500°C are possible depending upon the ratio of concentration and efficiency of the collector.[2] Flat-plate collectors use no or little concentration but merely collect the radiation falling on them. On a clear summer day temperatures of 100°C may be reached but usually only with difficulty. So for high efficiency SEUD concentrating collectors must be used. Low

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[2] Theoretically temperatures higher than 3500°C could be reached. I give this as a maximum because it is about the temperature achieved by the large solar furnace operated at Odeillo, France.

efficiency applications, for example the simple production of low-grade thermal energy, can use flat-plate collectors quite well. More about this in the section on flat-plate collectors.

Usually when someone hears about using the sun to generate electricity, solar cells spring immediately to mind. They are solid-state devices, not unlike transistors, that convert sunlight directly to electricity—there is no intervening heat engine. Solar cells have been used extensively and reliably to provide power for satellites, and, to a lesser extent, to provide power for earth-bound remote places where the cost of using and replacing batteries is too great. Now what about using solar cells for large scale commercial power production? Per kilowatt, they currently range in cost from at least \$1000 to \$3500 depending upon the type and its efficiency. Their lifetimes, that is the period of times that they can be expected to produce electricity, are contingent on the type of cells, but for those of longevity, 20 years is an optimistic figure. Since fossil-fueled or nuclear generating plants have a cost of about \$250, more or less, per kilowatt of installed generating capacity, solar cells still cost much more. Cadmium sulfide cells could be produced for about \$5 per m^2 in large quantities according to a recent estimate.[3] Given a maximum conversion efficiency of approximately

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[3] Terrastar Report by Auburn University Engineering Systems Design Summer Faculty Fellows, NASA, September, 1973, pp. 4-10.

6% for CdS cells made with thin film technology rather than by the laborious and expensive process of crystal growth, this amounts to a cost of roughly .86¢ per kilowatt-hour in Great Falls.[4] The calculation ignores the costs of distribution and energy storage, if any. Only the cost of producing the CdS cell is considered. Estimations f installation and deterioration are difficult and most likely would be unreliable, so I haven't included them. Also a 10 year life expectancy is too high--5 years may be a better estimate considering current technology, thus doubling the cost per kilowatt-hour. Even so, CdS solar cells may not be too far from economic feasibility.

These solar cells are presently being used in Solar House I, a project of Maria Telkes and the solar energy people at the Institute of Energy Conversion. The cells serve a dual purpose. They produce quite a lot of heat during operation so that it is possible to circulate air under their backside and remove the heat for use in space heating. The cells are an integral part of the roof, making it possible to build air ducts underneath them. Unfortunately, the report from the Institute at the University of Delaware is not yet available.

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[4] At an average insolation rate per day of 525 langleys, about the correct figure for Phoenix, Arizona, a 6% conversion efficiency would yield ~134 hwhr/yr for a fixed horizontal cell. The corresponding value for Great Falls is ~95 kwhr/m^2. The cost is figured for a capital investment of \$5 per m^2 at 10% simple interest and a 10 year amortization period. Also 6% is a bit high for the conversion efficiency.

Another idea for using solar cells from Peter Glaser. He suggests establishing in a stationary orbit about the earth a large array of solar cells and mirrors for reflecting additional light onto them.[5] The power that they generate could be beamed via microwaves to a receiver on earth where it would again be converted to electricity. The notion is that solar cells could produce more power per unit area of cell without the intervening layer of atmosphere and also could produce power almost continuously if the orbit is not in the equatorial plane. Of course, the expense of establishing such a power station would be immense, even if the cost of solar cells is reduced. Furthermore, there are ecological objections. The global heat balance would be upset by the addition of energy which the earth would normally not receive because the power received from the station would eventually deteriorate to thermal energy. Unless precautions were taken to prevent it, the average temperature of the earth would rise. Anyway, the establishment of such a station is in the distant future.

It is clear that the direct conversion of sunlight to electricity is not yet economically feasible on a large scale. However, with advances in the technology of making solar cells, specifically CdS solar cells, some application on a commercial scale might be possible.

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[5] Peter Glaser, "The Use of the Space Shuttle to Support Large Space Power Generation Systems," Presented at the Meeting of the Astronautical Society, December 26-31, 1972, Washington, D.C.

The alternative to directly converting sunlight to electricity via solar cells, as you might already have guessed, is the use of focusing collectors to produce steam then using the steam in a conventional steam turbine and generator. Focusing collectors would not be essential to produce steam from sunlight--flat-plate collectors could also be employed. But as I have previously demonstrated, focusing collectors are an economic necessity for large-scale power generation because of the higher temperatures, ergo higher efficiencies, that they can produce.

A focusing or concentrating collector is some device which gathers the sunlight from a large area and concentrates it onto a small area. Because of their nature, they are able to utilize only the direct beam component of sunlight. Diffuse light cannot be focused. So before any estimates of the performance of a system using this sort of a collector can be made, the direct beam component of sunlight must either be measured or found by calculation. Unfortunately, only very few places in the U.S. are equipped for such measurement as I've previously mentioned. Equally unfortunate is the fact that there is no completely accurate way of calculating it. Nevertheless, I made a couple of attempts at estimating direct beam radiation on a surface always oriented so that it faces the

sun. For Great Falls the two estimates are 5.14×10^5 and langleys yr^{-1} (see appendix 2).[6]

Now what sort of a device is it that can use only the direct beam component of sunlight and produces temperatures high enough for use with a steam turbine? There are several types (see figure 1 for a schematic of the apparatus). One consists of a system of many plane mirrors continuously oriented so that they can reflect the maximum amount of sunlight falling over a large area to a central collection point where a receiver or boiler is located. Some fluid, water for example, circulates through the receiver, is vaporized at high temperature and pressure, and is then used as the working fluid in a turbine and generator set-up. In fact such a plant, three of them at last count, has already been constructed by G. Francia of the University of Genoa, Italy. The third produces 150 kg of steam at 500°C and 150 atmospheres pressure per hour of bright sunlight by concentrating the sunlight from 200 m^2 of mirrors onto an overhead receiver. Unfortunately such a geometry does not readily lend itself to the construction of a larger capacity plant because of the problems inherent in the overhead suspension of a larger receiver.

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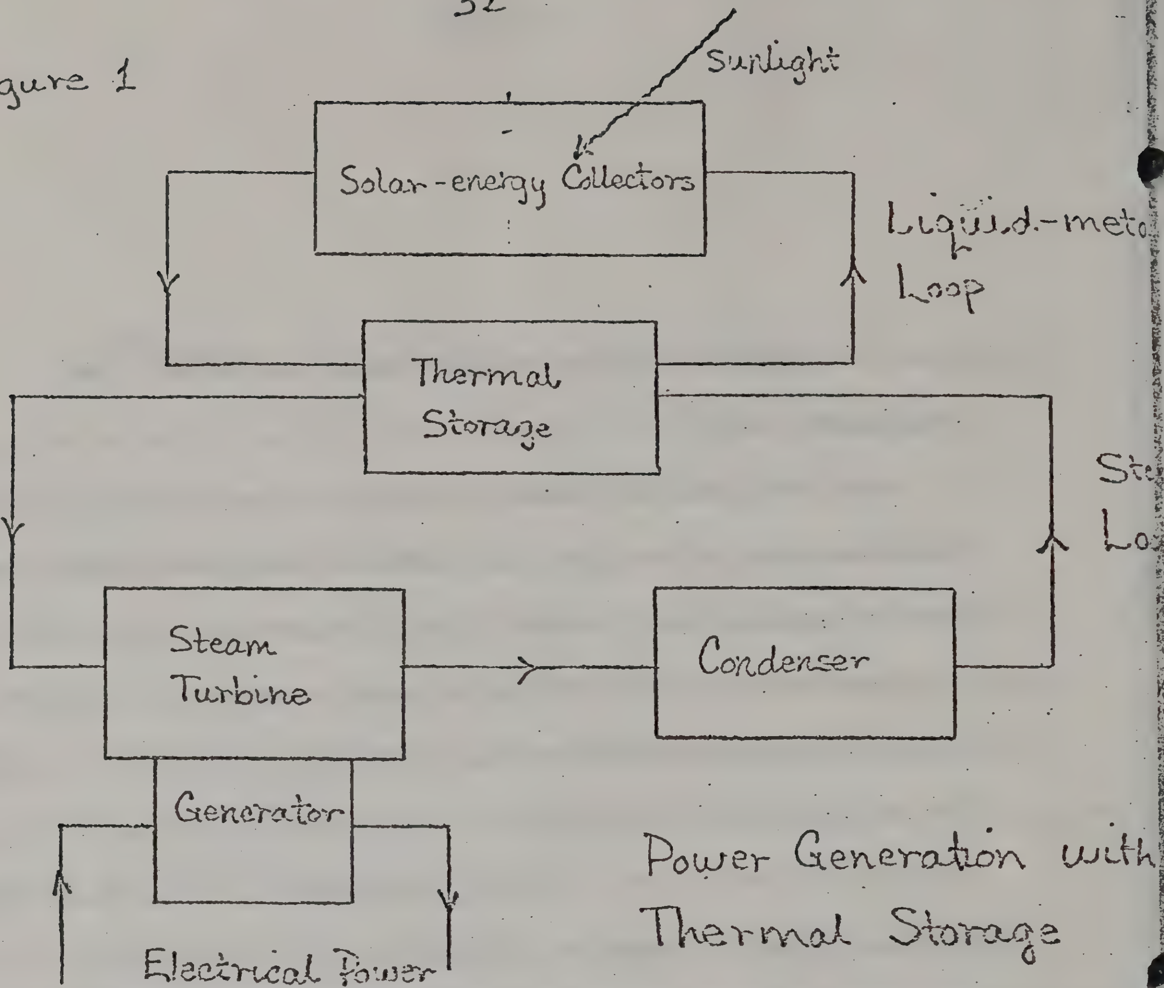
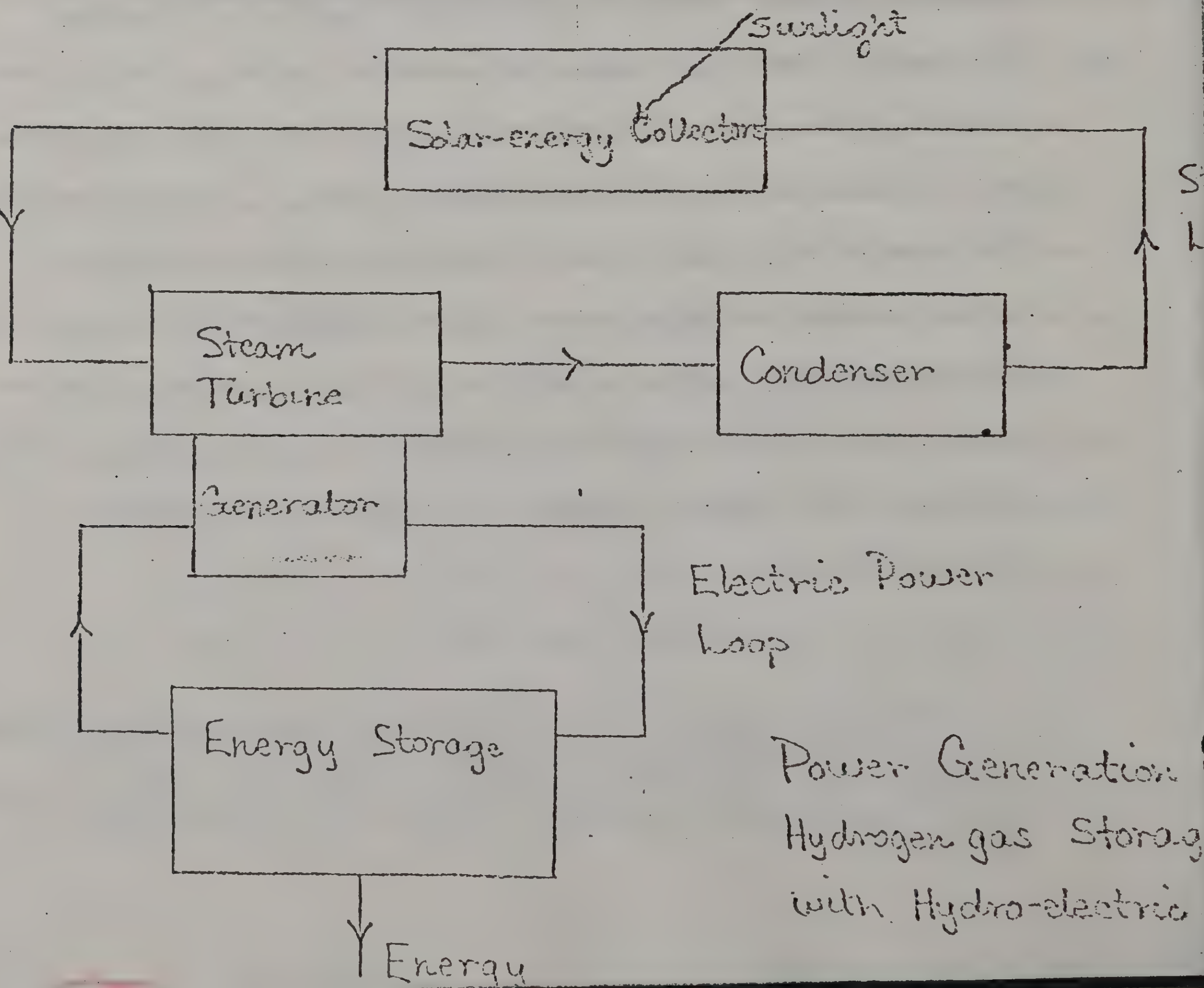
[6] The first estimate is the theoretical maximum energy delivered to one cm^2 over one year. The second, calculated using actual insolation data and weather information, probably is closer to what the direct beam radiation really is. Neither of these estimates is trustworthy.

Figure 1



Power Generation with Thermal Storage



Power Generation
Hydrogen gas Storage
with Hydro-electric

But the Martin Marietta Corporation has designed a generating plant with similar geometry which will accommodate itself to larger capacities (see figures 2 and 3). They estimate the optical system and receiver (steam generator) of their design to be 60.8% efficient for operation at 540°C (~ 1000°F). Thus about 740 m^2 of heliostat mirrors could produce 100 kilowatts in conjunction with a 24% efficient steam turbine and generator.[7] The cost of a 1000 kw pilot plant is estimated to be $783,620 or $783.62 per kw of generating capacity, a cost considerably larger than for fossil-fueled or nuclear plants.[8] Undoubtedly, this cost could be reduced once experience is gained with tyis type of electric generation and the associated equipment becomes readily available.

Another similar configuration was discussed in a recent paper.[9] Plane mirrors are again continuously oriented to reflect sunlight onto a boiler mounted atop a 450 m tower. At 35 degrees latitude this device (see figure 4) could collect 2700 mw of heat per day in

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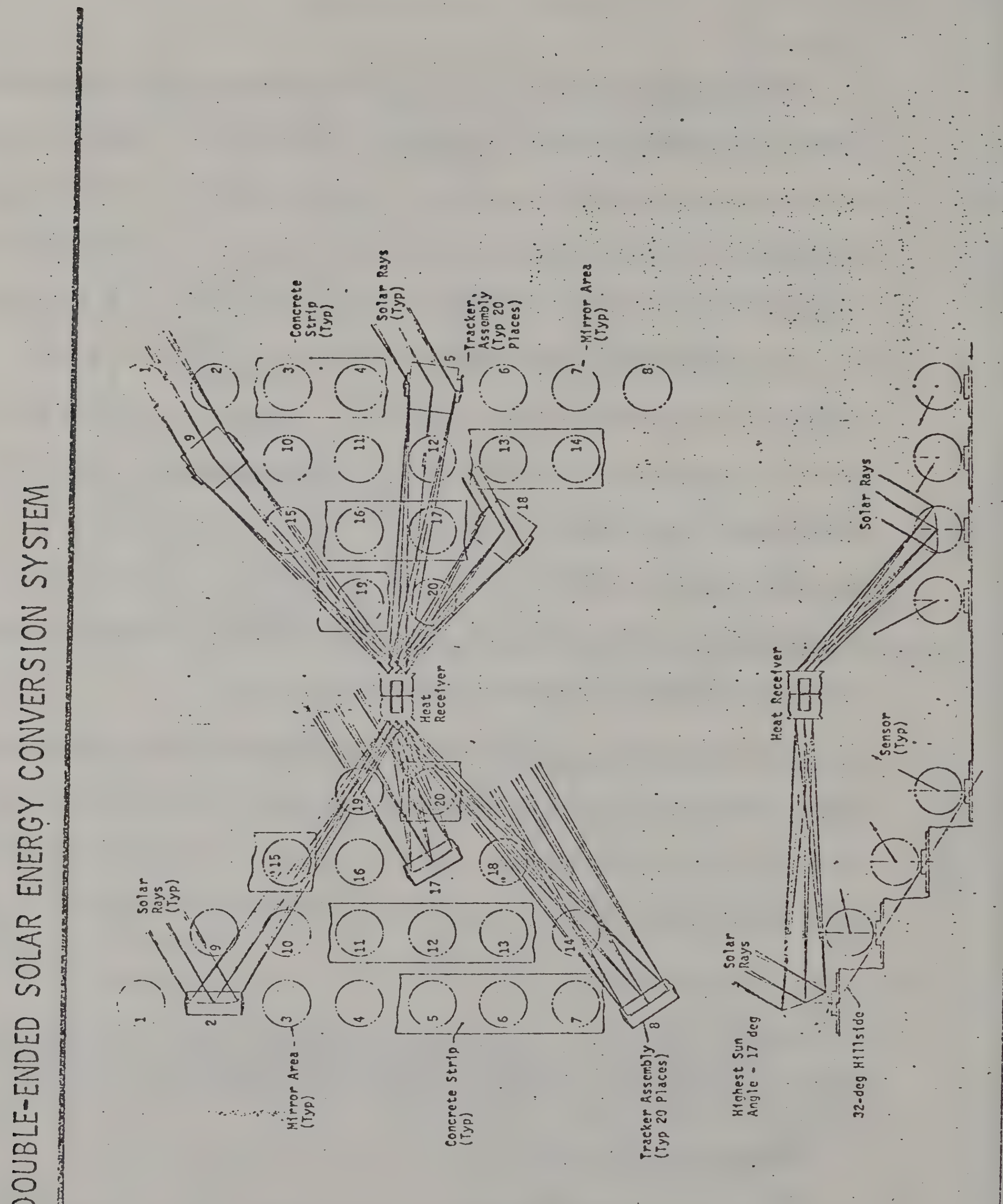
[7] Solar Power Conversion System and Applications, Presentation to Western Systems Co-ordinating Council, September 1973, Martin Marietta Corporation, p. 35.

[8] Ibid., p. 46.

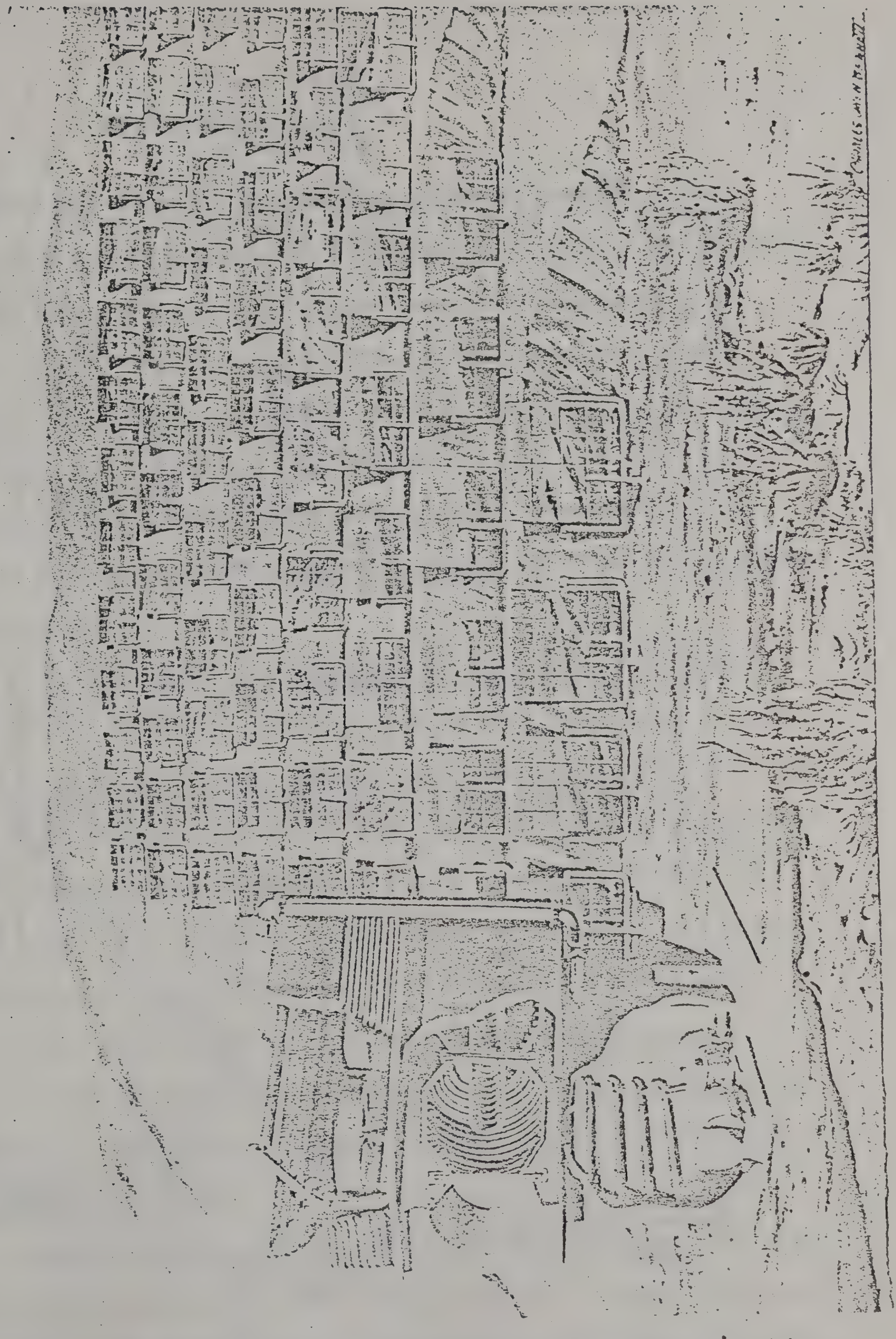
[9] A. F. Hildebrandt and L. L. Vant-Hull, "A Tower Top Focus Solar Energy Collector," ASME Paper No. 73-WA/SOL-7 (November, 1972).

Figure 2



From <u>Solar Power Conversion System and Applicati</u>
p.6.

Figure 3



NORTH-SIDE FIELD OF 1000-kWe SOLAR POWER SYSTEM

From Solar Power Conversion System and Applications, p. 57.

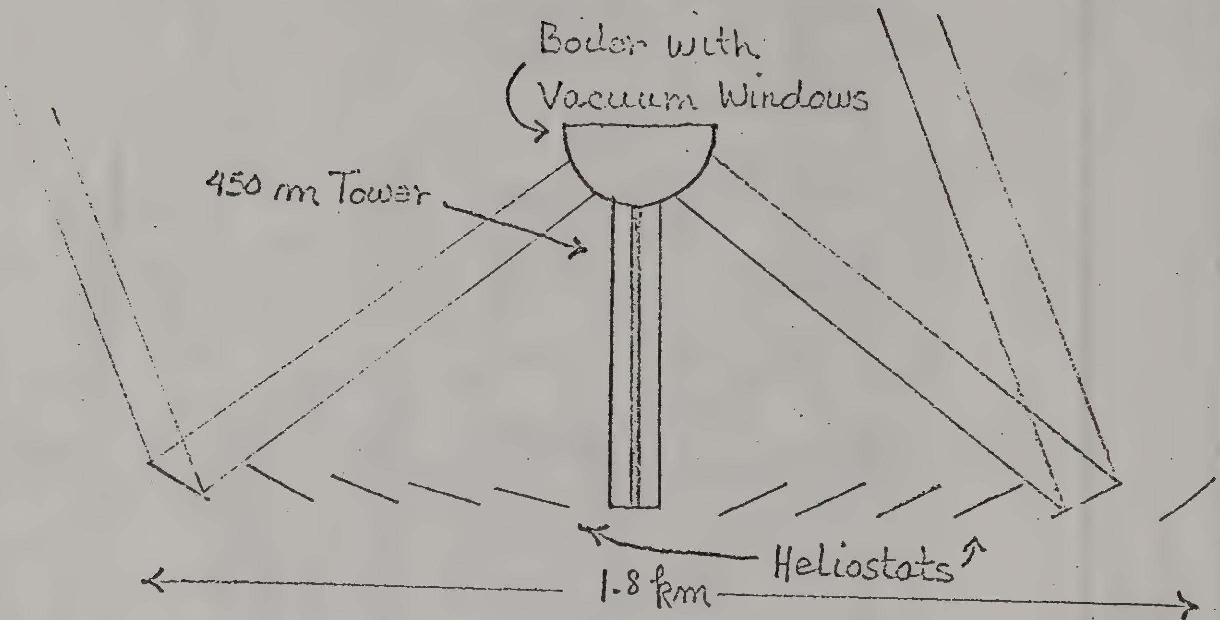


Figure 4

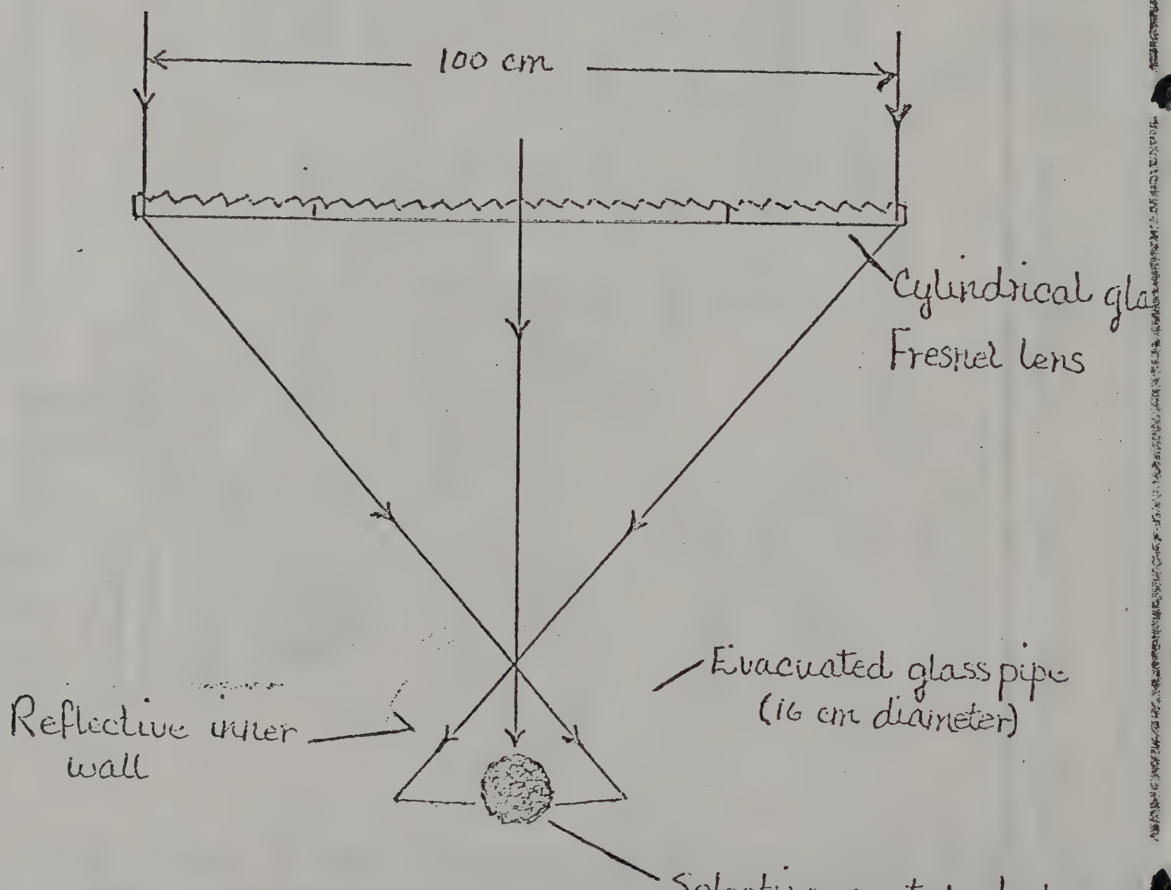


Figure 5

midwinter and about twice as much in midsummer from a 2.6 km^2 field, 45% of which is covered with plane mirrors. At the 26% conversion efficiency which the authors estimate, this amounts to 702 mw and 1404 mw of electricity for midwinter and midsummer, respectively. Figuring the total cost of the installation to be $4,400,000 and a year's energy production to be 1731 x 10^6 kwhr of heat or 4.5 x 10^8 kwhr of electricity, this reduces to .254¢ per kwhr of heat or .98¢ per kwhr of electricity, still somewhat expensive but not prohibitively.

V. A. Baum, a Russian solar energy researcher, had a similar idea several years ago. Instead of stationary heliostats, he proposed using railroad flat cars with plane mirrors on them. The flat cars would move with the sun so that sunlight is always reflected onto a boiler, again mounted on top of a tower. A one-fiftieth scale model of it was built and performed as expected. The major technical problem with these last two proposals is reducing the heat losses from the boiler. It may be necessary to evacuate an enclosure around it so that conduction and convection losses are minimized. That would, of course, increase the cost of building the generating plant.

There is another general type of thermal power plant that has been seriously advocated. This one uses linear focusing collectors of which figure 5 illustrates a cross-section (the Fresnel lens may

be replaced by a trough-like parabolic or cylindrical reflector depending on which proves to be less expensive). Large arrays of these collectors are deployed to concentrate the incident sunlight on steel pipe in the center of each. A liquid metal, such as sodium, is pumped through the pipes to remove the heat as it accumulates. The hot sodium is stored in insulated tanks from which heat is drawn to operate a conventional steam turbine. The reservoirs of liquid metal would store enough heat to operate the plant during cloudy spells and at night. Additionally, the waste heat from the generating plant would be used to de-salinate water for use in arid or semi-arid areas. The Meinels at the University of Arizona, to whom this brainstorm belongs, have proposed the construction of just such a plant near Yuma, Arizona, where the clear skies would make its operation most economical. But the economics of it, even with the 330 clear days per year that the country around Yuma average, are not altogether favorable. The Meinels say that given a 30% overall efficiency, a cost of \$60 per m^2 for both the collectors and storage system, an interest rate of 10%, amortization over 15 years and a 40 year lifetime for the entire system, the electricity generated would cost about 55¢ per kwhr.[10] The tenuous point is the \$60 cost for collectors and storage--presently it probably could not be met.

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[10] Aden B. Meinel and Marjorie P. Meinel, "Physics Looks at Solar Energy," Physics Today, XXV: 2 (February 1972), pp. 49-50.

Their scheme isn't so wild, however. Around 1913 a similar system using water as an operating fluid was built and used to operate a 50 hp steam engine for an irrigation pump in Cairo, Egypt. If it could be done in 1913, it can certainly be done today.

After this rather disappointing excursion into thermal conversion systems, what can be said about the future of it? Successful and economic thermal power generation depends largely on technical developments and also on the increasing cost of conventional power. If collectors can be cheaply produced and there is a concomitant breakthrough in thin films production necessary for achieving high collector efficiencies (see the section on thin films), then thermal conversion of sunlight into electricity will no doubt be looked on as more practical. But none of these breakthroughs will occur unless some interested body actively pursues them. Even if pilot plants were built today, betting that in the future the knowledge gained by their operation would be useful if not essential, and assuming that the effort to develop solar power proceeded full steam ahead beginning immediately, solar energy could make scarcely a dent to the total power produced in this country for more than a decade. The lesson to be learned: research and development of solar energy for power production must begin now!

selective surfaces

Now I would like to briefly discuss a key technology to most all applications of solar energy, namely, selective surfaces. As you might remember from the section about the sun where I mentioned that the sun is essentially a black body, I also said that any body with a temperature above absolute zero radiates energy to its surroundings, and if the body and its surroundings are in thermal equilibrium (both have the same temperature), then the body's surroundings give an equal amount of energy right back. But if the body, say a solar collector, is at a temperature greater than the ambient temperature, it loses energy to its environment. This we would like to prevent since we want to extract as much energy as possible from the solar collector. Some of the energy loss can be prevented by stopping conduction and convection through proper insulation, but inevitably some energy must be lost by radiation. How can this be prevented or inhibited?

Let's imagine that the collecting surface of the solar collector radiates as a perfect black-body at temperature T_C. Of course it doesn't radiate this way, but for our purposes the approximation will suffice. Now T_C will be some temperature much lower than the temperature of the sun which is about 6000°K. If we plot the relative

intensity of the sun and the relative intensity of the solar collector versus wavelength on the same graph, we get a picture like that in figure 1. We see that the major part of the sun's energy is radiated at different wavelengths than the solar collector's is. Thus, if there is some way to inhibit energy losses which occur at longer wavelengths but at the same time absorbing energy at shorter wavelengths, we could collect more of the sun's energy and have a more efficient collector.

Let's back up just a bit. Everyone has noticed that on sunny days black objects are warmer than lighter colored things. That's reasonable since black things absorb more light than others. If an object is made black by coating so thinly with black paint or some other black-like covering that the thickness of the coat is not so great as the wavelengths at which the body would ordinarily radiate the major portion of its energy, but thicker than the wavelengths of the major part of the sun's energy, then radiation by the body is inhibited, more energy is accumulated and, if we are removing the heat from the collector all along, we are enabled to remove more of it at a higher temperature.[1] Now the absorptance (or emittance) versus wavelength curve of the collector looks like figure 2--more energy is absorbed at short wavelengths and less

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Figure 1

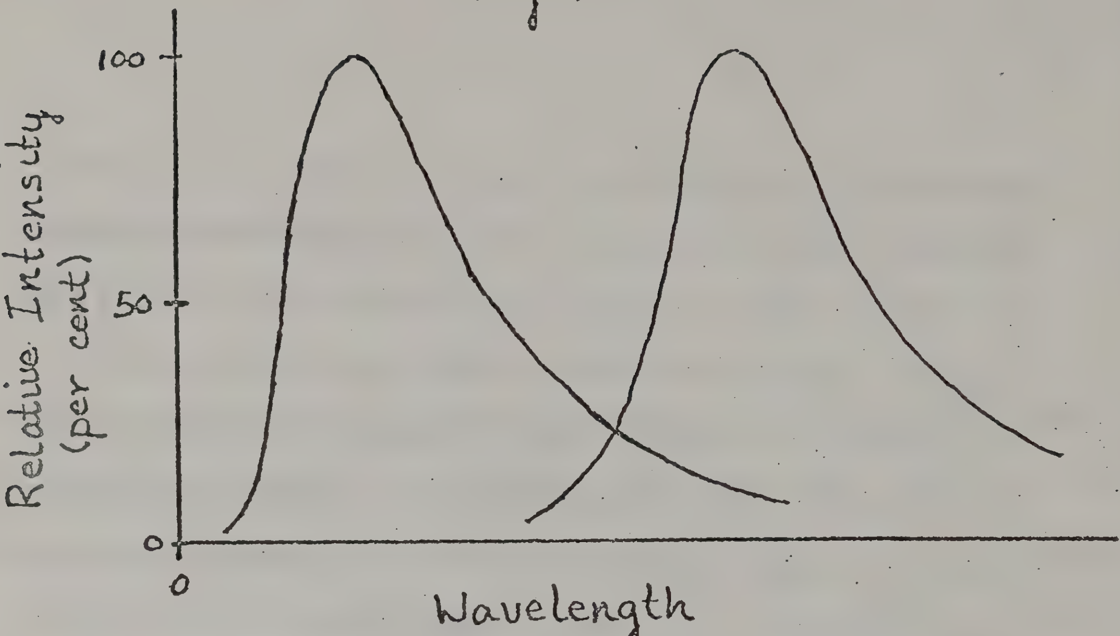
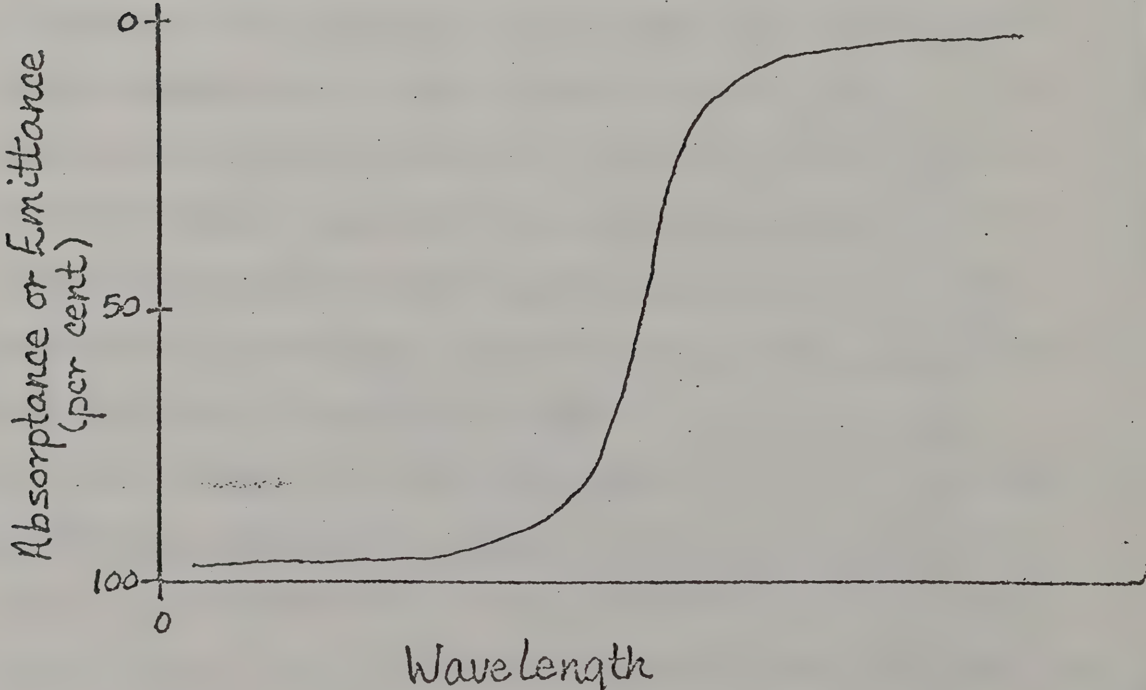


Figure 2



emitted at longer wavelengths. It looks as though a technique for depositing such a thin coating could be well worth the search.

Already there are methods for doing this, and depending on the expense to which a person wants to go, it can be done quite well. Absorptance-emittance ratios, commonly referred to as a/e ratios, express the ratio of the amount of energy absorbed by a body to that which it loses by emittance. A/e ratios as high as 99 have been obtained for certain specialized surfaces. But for bodies that attain any temperature substantially above ambient, these specialized surfaces are not famous for their longevity. Surfaces have been made that will withstand moderate temperatures for long periods and that have a/e ratios of 9. They are also not terribly expensive, and their costs will be reduced if demand warrants mass production of them. So if we coat our solar collector with one of these selective surfaces, we ought to get a better efficiency collector.

Solar power generation, such as the Meinel's scheme, requires a/e ratios of at least 10 to be economically feasible, and these surfaces must be able to withstand high temperatures for long periods of time. Such surfaces can be made now but not at a particularly favorable price. The difficulty of making a durable coating around 10^{-4} cm thick or finding some combination of materials that will give a high a/e ratio is not trivial. The techniques

of sputtering and thin film deposition must be improved before a/e ratios of 10 become widely available. When these selective surfaces do become easier to produce, and when surfaces with higher a/e ratios are available, it ought to be possible to reduce the size of a collector array and, hence, its cost and the cost of the energy it produces.

In table 1 are some selective surfaces such as might be used with a flat plate.

Table 1

Properties of Some Selective Surfaces for Solar Energy Application

α = absorptance for solar energy

ε = emittance for long wave radiation at temperatures typical of flat plate solar collectors

Surface	α	ε
"Nickel black" oxides and sulfides of Ni and Zn on polished Ni[1]	.91-.94	.11
*"Nickel black" on galvanized iron[2]	.89	.12-.18
CuO on anodized Al[3]	.85	.11
CuO on Ni, electrodeposition of Cu and subsequent oxidation[4]	.81	.17
CuO on Al, spray dilute $Cu(NO_3)_2$ solution on hot Al plate and bake[5]	.93	.11
*Ebanol C on Cu[6]	.90	.16
PbS crystals on Al[7]	.89	.20

$Al_2O_3-Mo-Al_2O_3-Mo-Al_2O_3-Mo-Al_2O_3$ interference layers on Mo ($\mathcal{E}$ measured at 500° F)[8]	.91	.085
"Nickel black", two layers electroplated on mild steel[9]	.94	.07

* indicates commercial processes

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[1] H. Tabor, "Selective Surfaces for Solar Collectors," Low Temperature Engineering Applications of Solar Energy, (New York, 1964), pp. 43-46.

[2] Ibid.

[3] Ibid.

[4] P. Kokoropoulos et. al, "Selective Radiation Coatings: Preparation and High Temperature Stability," Solar Energy, III:4 (1959), p. 19.

[5] H.C. Hottel and T.A. Unger, "The Properties of a Copper Oxide-Aluminum Selective Black Surface Absorber of Solar Energy," Solar Energy, III:3 (1959),

[6] D.K. Edwards et al., "Basic Studies on the Use and Control of Solar Energy," Report No. 60-93, Department of Engineering, University of California, (October, 1960).

[7] D. A. Williams, T. A. Lappin and J. A. Duffie, "Selective Radiation Properties of Particulate Coatings," Transactions of the ASME, 85A (1963), p. 213.

[8] R. N. Schmidt, K. C. Park and E. Janssen, "High Temperature Solar Absorber Coatings, Part II," Technical Document Report No. ML-TDR-64-250 from Honeywell Research Center to Air Force Materials Laboratory, (September, 1964).

[9] John A. Duffie and William A. Beckman, Solar Energy Thermal Processes, Personal communication to R. N. Schmidt, Honeywell, Corp., (Solar Energy Laboratory, University of Wisconsin, Madison, Wisconsin, 1974), p. 5.23.

energy storage

One of the major objections to solar energy is its intermittency. In order for energy from the sun to be constantly available, some method of storing the energy produced while the sun shines or while the wind blows must be devised. This can be done in several ways—which way will depend on the sort of solar energy system in use and in what form the energy is ultimately wanted.

Let's consider systems for electricity production first. Using the Meinels' scheme, heat is stored in a molten salt or liquid metal and contained in large insulated tanks for use at night or during cloudy spells. Depending upon the type of material, large quantities of thermal energy at high temperatures could be accumulated. Then, when the sun disappears, the heat in the molten salt or liquid metal reservoir is used to produce steam for the turbines. This sort of energy storage could be used equally well with any of the other methods for thermal power generation that I've previously sketched; in fact, it has advantages over using water as the heat transfer medium. There would be no problems associated with high pressures inherent to high temperature and high pressure steam. The technology of using liquid sodium as a heat transfer fluid is

already being developed for use in nuclear reactors. There is no reason why it can't be used equally as well in a solar energy power station.[1]

An alternative to storing thermal energy is storing the electricity. It could be stored directly in storage batteries, used to pump water into a reservoir and later the stored water used for hydro-electric generation, or the electricity could electrolyze water into hydrogen and oxygen, the hydrogen later being used like natural gas or both the hydrogen and oxygen used in a fuel cell. The first alternative is probably limited to small-scale electric production such as storing the energy output of a small windmill or a small array of solar cells. The price of lead-acid batteries designed for use with a 2000-watt wind generator is $475.[2,3] These batteries can typically withstand some 2000 complete cycles of charging and re-charging and at full charge hold 130 amp-hr or 14.95 kwhr at 115 volts. Let's see what the maximum cost of storage is based on 2000 cycles of charging and re-charging.[4] If the

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[1]Unfortunately, I wasn't able to come up with a cost estimate for storing energy this way.

[2]Price quoted from Electric Power from the Wind by Henry Clews, p. 18.

[3]The cost of lead-acid batteries remains fairly constant for any size installation. Thus, little, if any, savings are realized for larger installations. See Direct Use of the Sun's Energy by F. Daniels, p. 241.

batteries last 15-20 years, as their manufacturer claims, and the cost of them is amortized at 10% interest over 10 years, this leads to a storage cost of more than 3¢ per kwhr. For a relatively small windmill, the size a homeowner might use, perhaps the cost is not too oppressive since his electricity from a power company costs about 4¢ per kwhr. Also, if these batteries were to be produced in large quantities, their cost would drop.

The second alternative is already used by power companies to store energy for use during periods of peak demand. Excess electricity produced in slack periods is used to pump water into a reservoir, then at times when demand exceeds the capacity of the company's other generating plants, energy production is supplemented by hydro-electric generation with the stored water. This whole system is rather inefficient in terms of the energy expended to deliver electricity to the consumer, but its costs are not exorbitant. The generating plant should also be located near a place where there is enough water for storage.

Lastly, water can be electrolyzed to hydrogen and oxygen and the two gases employed with a fuel cell, or hydrogen can be used by itself much like natural gas. Hydrogen-oxygen fuel cells have

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[4]Actually more energy could be stored since the batteries won't be completely discharged every time they are used. So the cost per kwhr ought to be less but since the amount of energy withdrawn is difficult to estimate, we'll use 2000 cycles for ease of argument.

use to store heat at low temperatures. In addition, the heat of fusion of some chemicals has been exploited for heat storage. Each of these methods has advantages relative to the others. Rocks are inexpensive but rather bulky. With a heat capacity of 9.30 $kwhr/m^3$ at 20°C it would take about 35 m^3 of rock to hold enough heat to maintain an average size house[7] at 21°C (70°F) for one day when the outside temperature is -18°C (0°F). That is over 150 ft^2 of floor space. On their plus side, rock storage beds do have good heat transfer between rock and air, but again on the negative side, heat cannot be added to the storage bed and taken out at the same time.

Using water storage on the other hand allows heat to be added to storage and removed concurrently. It is still a cheap storage medium and has a high heat capacity (4.19 kl/kg°C). So to store one day's heat for the same house and conditions as above, we need 5.4 m^3 of water at 70°C, a much smaller volume. More will be said about this sort of heat storage later.

Lastly, chemicals are used for heat storage. All solids absorb some specific quantity of heat without a corresponding rise in temperature when they are melting, and conversely the liquid, when it solidifies, gives up an equivalent amount of heat. This heat

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[7]Here as throughout the paper I take an average size house to mean a heat load of 1200 kl/hr-C° or 15,178 BTU/DD.

relatively high efficiencies (about 60%), but at present their cost is too high to be competitive with other means of storage or generating electricity. Using hydrogen directly for heating, generating electricity or even in internal combustion engines could prove to be a viable way of energy storage depending on the cost of producing it.[5] The modifications required to convert a natural gas system to hydrogen are simple and inexpensive. Another advantage is that combustion of hydrogen is almost non-polluting, yielding lots of water and nitrous oxides in low concentrations.[6] The one disadvantage to hydrogen as a fuel is its bulk. Per unit volume hydrogen contains much less energy potential than natural gas (1210 kJ/m^3. But hydrogen could be liquified for use in cars thus increasing the energy potential per unit volume. There are problems in keeping hydrogen liquid since it has such a low boiling point, but they are not insurmountable, only expensive at present. It would be possible to convert a hydrocarbon fuel economy to hydrogen fuel without tremendous problems.

Energy storage for solar systems producing low grade is less of a problem. As you will see in the chapter on solar space heating, the heat capacity of rock and of water have already been put to good

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[5] See "The Cleaning of America" by Larence Williams in the February, 1972, Astronautics and Aeronautics.

[6] At the optimum air-hydrogen mixture about one part nitrogen compound to 10^{14} parts air. See Williams, p. 45.

is usually referred to as the latent heat of fusion. If we could find some material that melts at a temperature within the range of our collector, the heat from the collector could be used to melt the material. Then when we need heat and the collector can't supply it, we simply let the liquid solidify and use the heat that the process of solidification liberates. There are several such suitable materials, a few of which are listed in table 1.

Maria Telkes has long advocated the use of such a method of heat storage because its larger heat capacity permits economy of container and space. In the University of Delaware's Solar House project latent heat storage is used. Previously there have been problems with crystallization of the material after many cycles of dissolution and solidification, but Telkes claims that the problems have been solved in the latest edition of the solar house. If so, the relative cheapness of Glauber's salt would permit heat to be stored in the relatively small space. Using the above example and disregarding any heat stored in the liquid itself, we find that $15.4\ m^3$ of Glauber's salt could store the day's heat. Using the Cl_2-$MgCl_2$-H_2O compound, the space required is even less--only $4.4\ m^3$.

Table 1

Material	Melting Point °C	Latent Heat KJ/Kg
$NaSO_4 \cdot 10H_2O$	32.3	49.9
$CaCl_2 - MgCl_2 - H_2O$ 41 10 49	25	175
Urea $- NH_4NO_3$ 45.3 54.7	46	172
$Mg(NO_3)_2 \cdot 6H_2O - AL(NO_3) \cdot 9H_2O$ 53 47	61	148

The numbers below the materials indicate the percentage of the compound by weight that the material contains. After Duffie and Beckman in <u>Solar Energy Thermal Processes</u>.

heating and cooling with the sun, flat-plate sunlight collectors, and associated paraphenalia

Finally, we've come to the application of solar energy that has in the past been most widely used and will be even more extensively used in the future. In the United States and several other countries houses have been at least partially heated with an array of flat-plate solar collectors and a heat storage system, and, paradoxically enough, some have been cooled using solar energy. Also, many sunny climates are put to work for heating water, both for home and industrial use. The heat produced this way has proved in the past to be more expensive than conventionally-made heat (or refrigeration) especially in industrialized countries. But as Tybout and Löf and others showed, there is in many climates an optimum combination of solar and conventional heat that gives least cost energy even in industrialized regions.[1] It seems reasonable to expect that as natural gas, fuel oil and electricity increase in cost, solar energy, which is always free, will become economically more attractive.

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[1] For example, see Richard Tybout and George Löf's "Solar House Heating" in the Natural Resources Journal, H. Buchberg and J. R. Roulet's "Simulation and Optimization of Solar Collection and Storage for House Heating" in Solar Energy, or "Simulation of a Solar Heating and Cooling System" by L. W. Butz, W. A. Beckman and J. A. Duffie among others.

Now a short elucidation of flat-plate collectors. Basically they are a device for generating low-grade thermal energy, that is, heat that's not very hot. The principle it operates on is the same as that which causes a car with its windows shut to heat up on a sunny day: sun shines through the windows and heats up the interior, but the windows, being relatively opaque to low temperature radiant energy, trap some of the sun's energy thereby raising the interior temperature. So to get low grade heat from the sun, we need only build a device that will do the same thing although we would like it to be a more efficient energy producer. In the past these more efficient collectors have been built thus: first we need a flat plate with good heat conduction properties and preferably with the sun-facing side darkened. Around the plate we construct an insulated box, and on the side that faced the sun we put a glass window. Now if we make provision for a fluid to circulate through the box, we can remove the heat that accumulates in it and pipe heat to wherever we want to use it. That is essentially all there is to a flat-plate collector.[2] Most likely we will want to embellish the collection system with facilities for heat storage, a selective surface on the flat plate and perhaps more than one glass pane on

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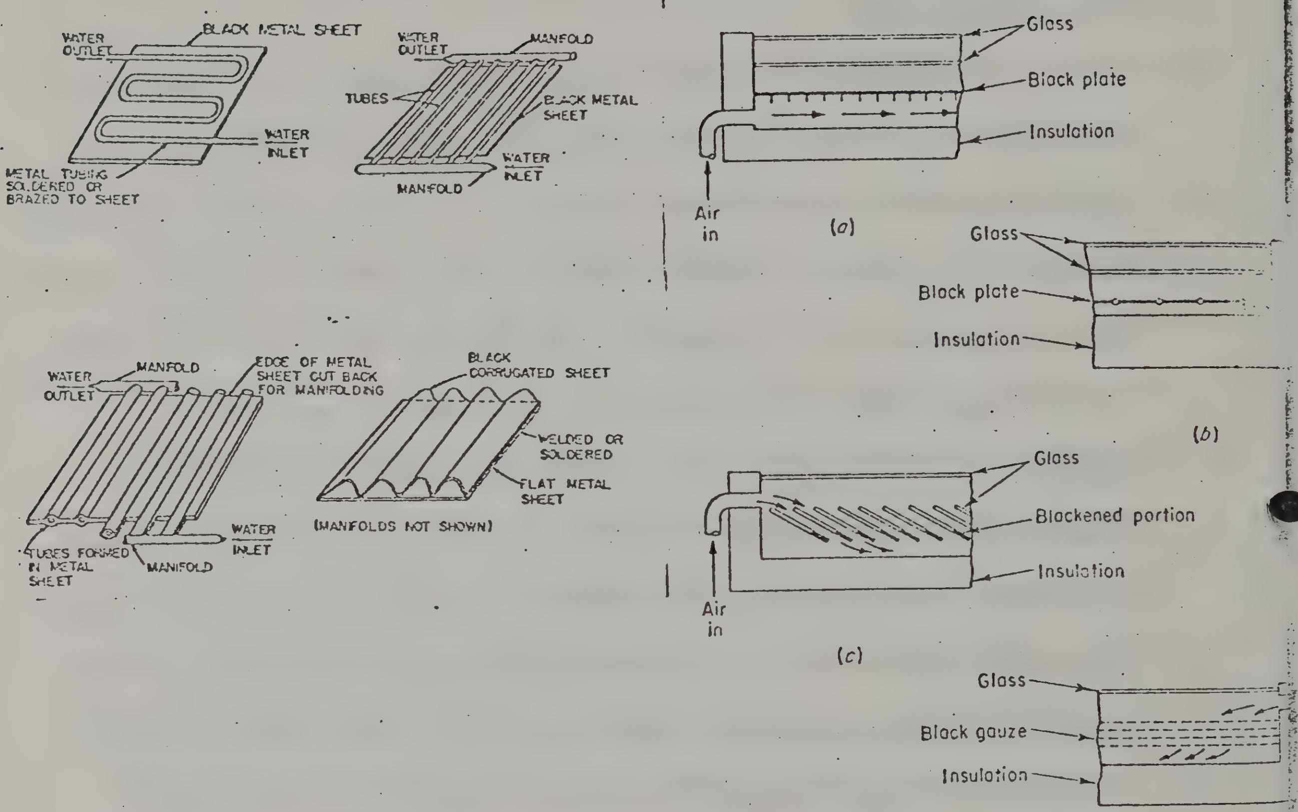
[2]Actually flat plate collectors don't necessarily need all these accouterments. In suitable climates the insulated box and the glass windows could be done away with. But Montana is not such a suitable climate, so we'll discuss only this general type of collector.

the collector's sun-facing side. In fact for economic operation of a flat plate collection system, one or more of these embellishments may be necessary.

It is important to note that unlike focusing collectors which are able to use only the direct beam component of sunlight, flat plate collectors can use both the direct beam and diffuse components. So even on completely overcast days it is possible to produce some heat by operating the collector. Exactly how much heat that could be extracted depends on the degree of cloudiness and ambient temperature. Also, flat plate collectors usually are fixed in orientation—they do not track the sun as focusing collectors must. The reason for this is quite simple: tracking apparatus is complicated and expensive and the quality and quantity of energy gotten from a flat plate collector does not warrant this extra expense.

So far I've outlined only the very basics of a flat plate collection system. There are many variations to it. For example, either water or air could be used as a heat transfer medium, rocks, chemicals or water could be used for heat storage (see the chapter on energy storage) or the geometry of the collecting surface could be altered to suit different needs. In figure 1 there are a few of the basic configurations illustrated.

Figure 1[3]



How have these things been used and how might they be used in the future? As aforementioned, it is possible to heat water, air and houses and even to cool them using a flat plate collector. The

[3] These figures are from Löf and Close, "Solar Water Heaters," Low Temperature Engineering Application of Solar Energy. (New York, 1967), p. 63, and Zarem and Erway, Introduction to the Utilization of Solar Energy. (New York, 1963), p. 88.

application I would like most to discuss is house- and hot water-heating. Obviously there are places in Montana that need cooling during the summer so I'll talk a little about that, too, but later. Let's start with some examples.

George Löf, whose name you see many times in the bibliography, designed a flat plate collector and heating system for his house in Denver, Colorado. It was designed as an integral part of the house. The flat plate heaters (see figures 2 and 3) warm air circulating through them which in turn warms rock storage beds or heats the house directly, depending upon current heat demand. In addition, the system pre-heats water for domestic use. His house is experimental, built to demonstrate that solar house heating really is feasible, but he also lives in it. Performance data was first gathered in the winter of 1959-60. It shows that the solar heating system supplied from 25% to 45% of the total heating load which was estimated to be 40,000 BTU per degree day.[4] The remainder of the heat was supplied by a natural gas furnace. The net savings for that winter were calculated to be $20.50 and $142.17 over the heating costs using only natural gas at 90¢ per 1000 ft^3 or using

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[4]George O. G. Löf, M. M. El Wakil and J. P. Chiou. "Design and Performance of Domestic Heating System Employing Solar Heated Air--The Colorado Solar House," Proceedings of the United Nations Conference on New Sources of Energy, Vol. 5 (New York, 1964), p. 192.

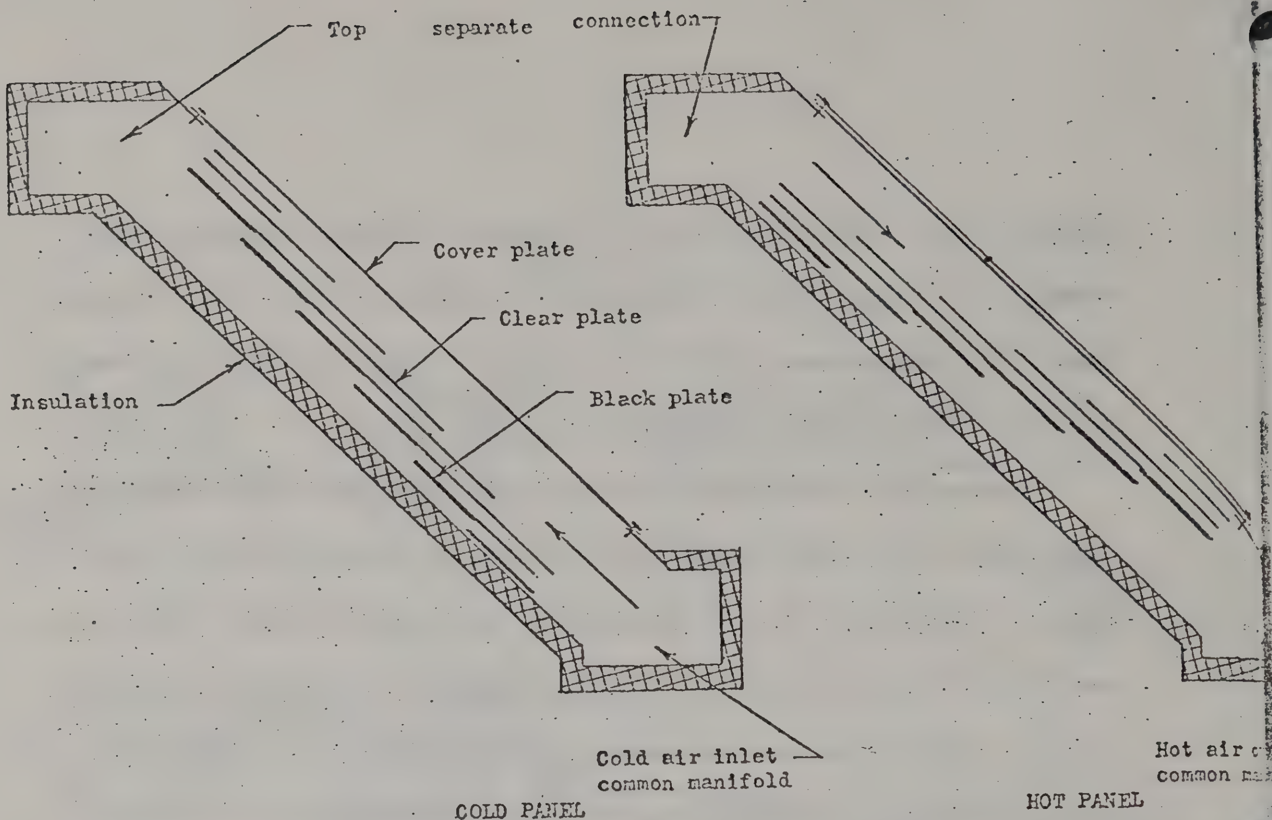
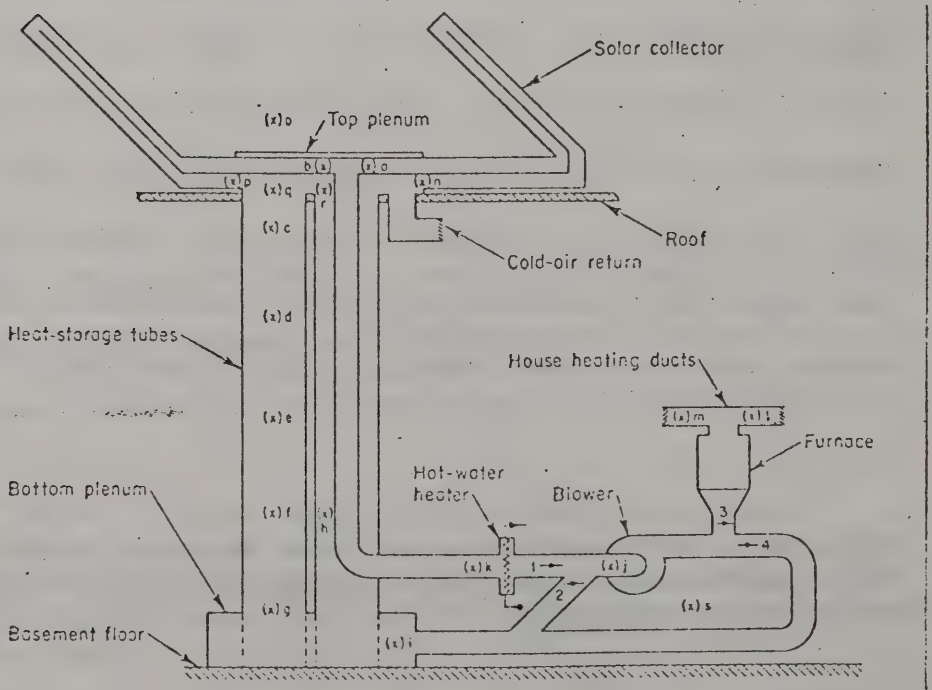


Figure 2[6]

Figure 3[7]



only fuel oil at \$1.50 per 10^6 BTU.[5] Löf estimated that the savings would be substantially greater if some minor changes were made in the heating system design and if the heat supplied for hot water during summer months was accounted for. But it must be noted that the cost of the solar heating system itself is not considered in figuring these savings, but rather the savings represent only the difference in cost between using all natural gas or all fuel oil instead of a combination of solar and natural gas heating. A more positive aspect of the system: since the house was built, the solar air heaters have operated essentially without maintenance. A few minor design flaws required correction, but after they were repaired, only periodic washing of the glass panes with a garden hose has been necessary.

Another house designed with a solar heating system was the M.I.T. solar house in Lexington, Massachusetts. Its collector was an integral part of the roof, tilted at 60° to the horizontal and with an area of 640 ft^2. (See figure 4 for detail of the collector.) The heat from the collector was stored in a water storage tank and supplemented by an oil-fired heater. The house itself was heated using an air-water heat exchanger with forced-air circulation (see figure 5). This solar heating system supplied considerably more of

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[5] Ibid., p. 193. The savings over natural gas heat at current Bozeman prices is over \$30.

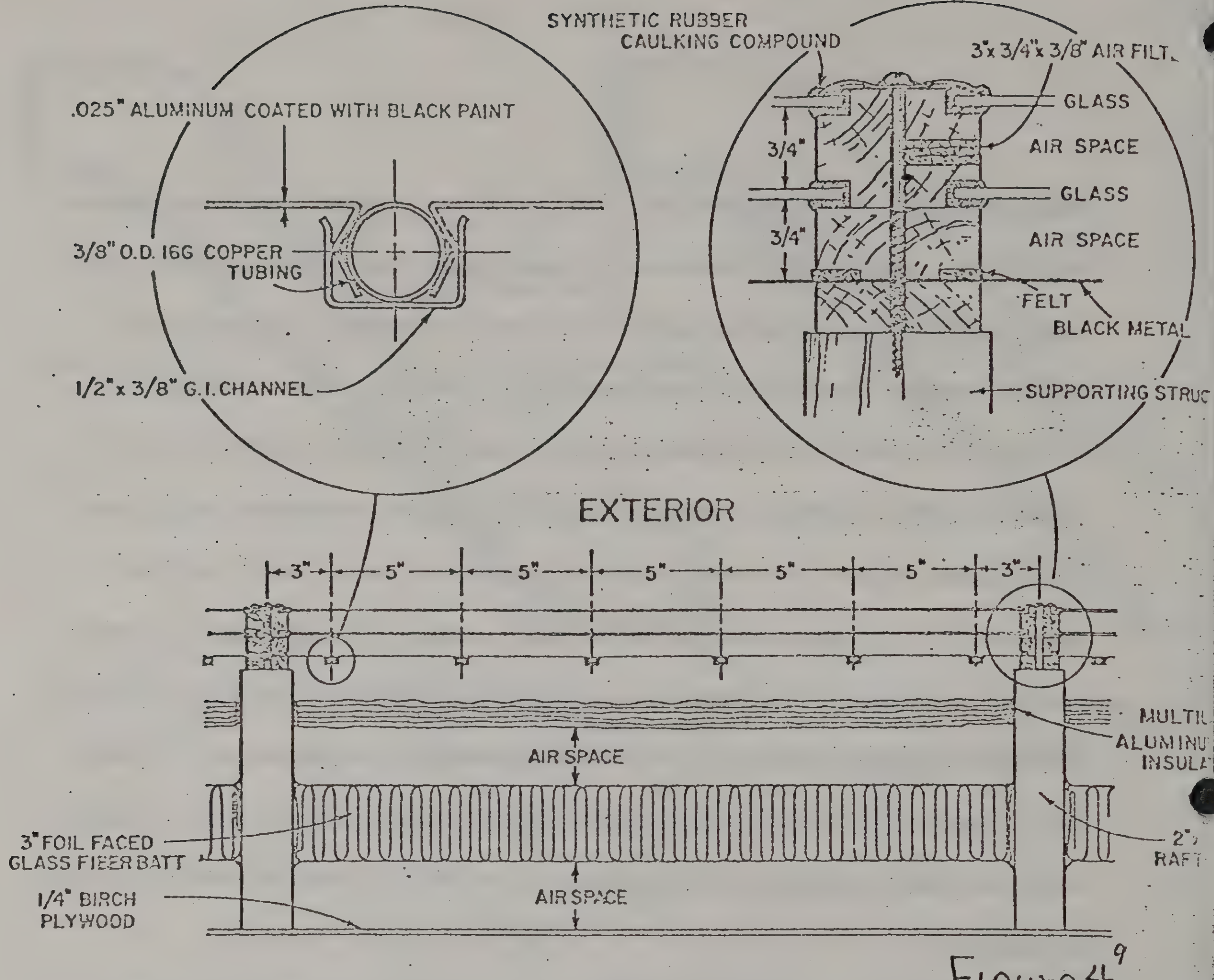

Figure 4[9]

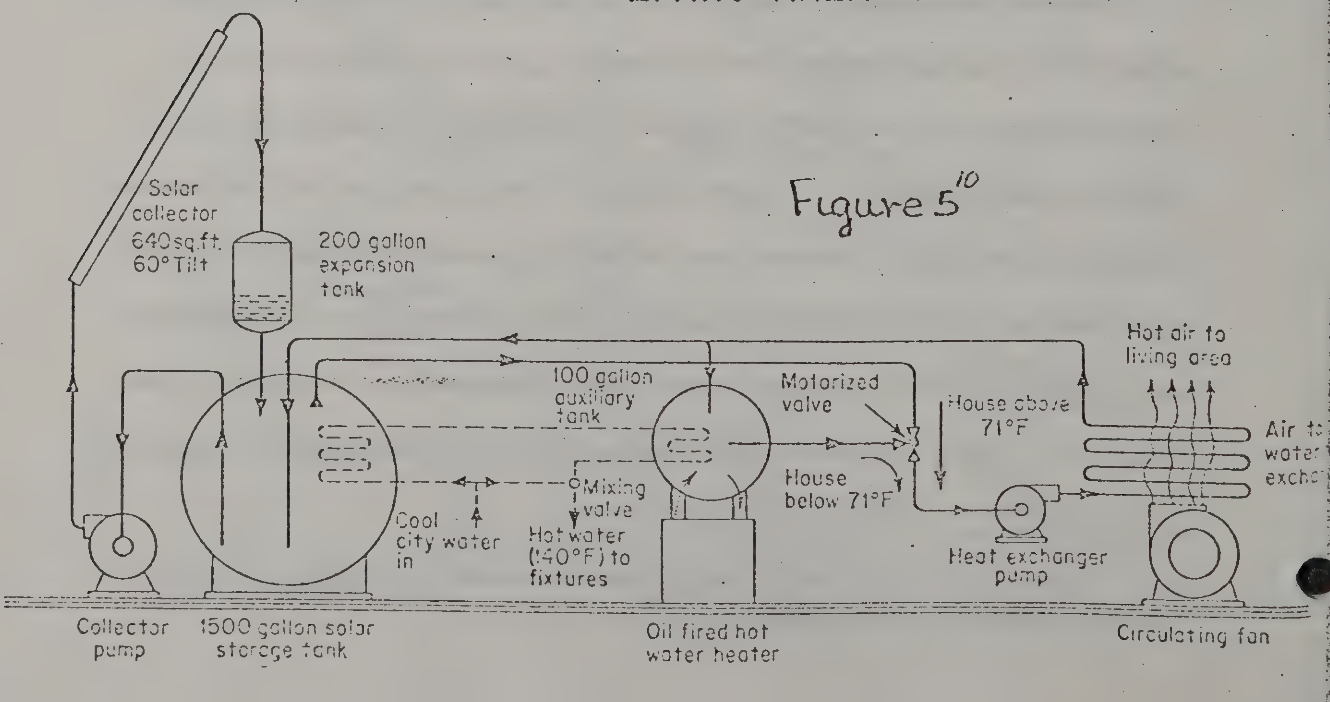

Figure 5[10]

the total heat load than Löf's system did--39.8 x 10^6 BTU of solar heat out of a total load of 82.8 x 10^6 BTU (48% solar heat) during the winter of 1959-60. In the six winter months of 1960-61 it supplied 47.4 x 10^6 BTU out of 83.7 x 10^6 BTU total (56.6% solar heat). More heat could have been supplied by the sun if the system had been larger--in fact 75% of the heat load or 62.8 x 10^6 BTU if the collector and storage tank had been 1.4 times larger in the winter of 1959-60 or 1.22 times larger in the 1960-61 heating season. No cost estimates were made for the heat produced by this installation.[8]

In Washington, D.C., Harry Thomasen has built two solar-heated houses that are unconventional by solar heating systems criteria. He simply constructed part of a south facing roof of blackened corrugated sheet metal. Water is pumped to the peak of the roof and allowed to slowly trickle down the incline on days with enough sunlight. The heated water is then stored in a water tank imbedded in a rock bed (see figure 6). The collector is 840 ft^2 for the first house he built and 560 ft^2 for the second, and the costs for

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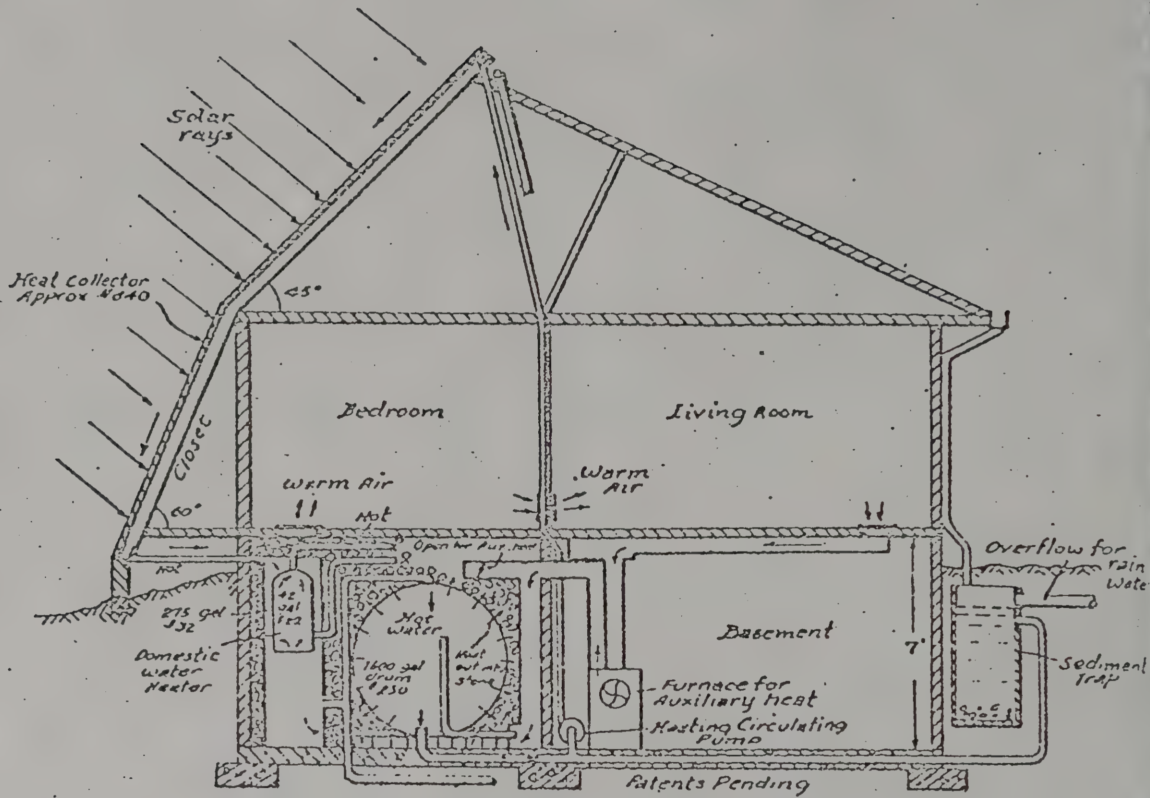
[6]Ibid., p. 187.

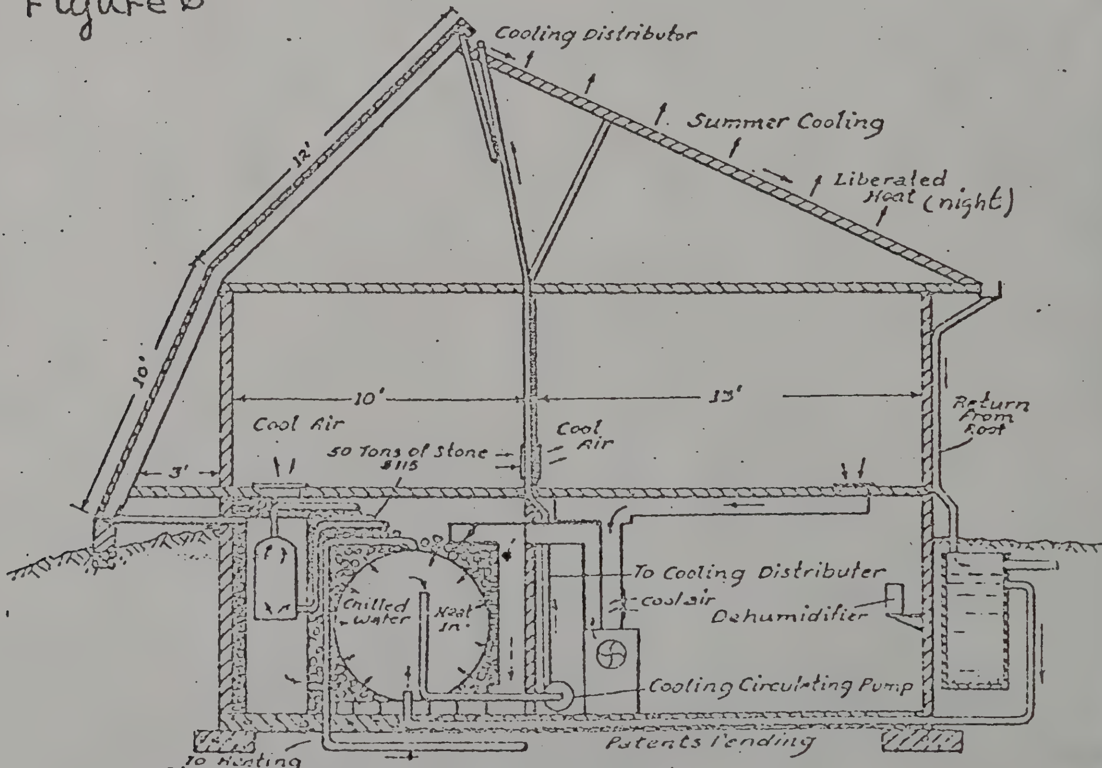
[7]A. M. Zarem and Duane Erway, Introduction to the Utilization of Solar Energy (New York, 1963), p. 272.

[8]C. D. Engebretson. "The Use of Solar Energy for Space Heating--M.I.T. Solar House IV," Proceedings of the United Nations Conference on New Sources of Energy, Vol. 5, (New York, 1964), pp. 159-172.



Winter Heating Cycle

Figure 6[14]



Summer Cooling Cycle

the entire systems were $2500 and $1900, respectively. The principal advantage to this type of collector is its reduced cost—$1.00-$1.25 per ft^2 compared to the usual cost of $2.50-$4.50 per ft^2 for the usual sort in an insulated box,[11] but, of course, the system is less efficient in terms of the actual amount of heat collected measured against the amount possible to collect. The houses weren't provided with any instrumentation for measuring the heat output of the system or for measuring any of the other variables necessary to accurately gage the performance of it. Nevertheless, Thomasen estimates its efficiency to be from 30% to 75% depending upon the temperature rise in the circulated water.[12] (The higher efficiency corresponds to less of a temperature rise in the heat collecting H_2O than the lower figure.) One indication of the success his design enjoyed is given by the cost of fuel for auxiliary heating—$4.65 (31 gallons of fuel oil) and $6.30 (42 gallons) for the winters of 1959-60 and 1960-61.[13] Thomasen evidently has plenty of confidence in his

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[9] Ibid., p. 162.

[10] Zarem and Erway, p. 269.

[11] Harry E. Thomasen. "Solar Space Heating, Water Heating, Cooling in the Thomasen Home," Proceedings of the United Nations Conference on New Sources of Energy (New York, 1964), p. 224. His first heating system has been in operation for over 14 years.

[12] Ibid., p. 226.

[13] Ibid., p. 227.

designs. He markets plans for similar solar-heated houses and has designed several other houses employing solar heating systems.

These three accounts far from deplete the number of houses and buildings using some sort of flat plate collector for space heating and cooling or for hot water heating. There are several more in the United States and the number is growing. There are quite a few projects under way to use solar heat for non-residential purposes. The Langley Research Center in Hampton, Virginia, will use 15,000 ft^2 of flat plate collectors to provide heat and hot water, and the Audubon Society plans to use solar heat in one of its buildings in Massachusetts. An entire community is being planned in California that will use solar heat. The company planning this community uses arrays of flat plate collectors for space and water heating, envisioning savings as high as 95% over conventional heat.

In the solar heating systems discussed you note that the buildings have all been designed with the collector system as an integral part. Thus the architectural and aesthetic problems associated with deploying large arrays of flat plate collectors can be designed out of the building. However, it is possible to add collectors after construction. As I showed previously even the roof of a house in Montana receives enough sunlight to heat the interior, provided that the collection system is sufficiently efficient. But for those of

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[14] Ibid., p. 225.

you who may perhaps be dreaming of doing this, it is necessary to add that the modifications needed in the present heating system and the building's structure may not be worth the trouble. This remains a problem for the individual dreamer.

A couple more designs, somewhat eccentric to the usual method of extracting heat from sunlight, but effective nevertheless: Steve Baer of Zomeworks Corporation in Albuquerque recycles 55 gallon oil drums by stacking them horizontally next to a glass wall with a southern exposure and filling them with water. The glass wall has a removable outer, insulated wall that is lowered during sunny weather so that the blackened ends of the barrels get the full benefit of the sun. Consequently, the water they contain is warmed. Then at night the insulated outer wall is raised into position against the glass wall and the accumulated heat that the water holds re-radiates into the house. During warm weather the system operates in reverse. At night the outer wall is lowered and the barrels lose heat to the cooler night sky by radiation. During the day the cooler water in the barrels absorbs heat from the house for radiation to the night sky again,[15] cooling the house as a result.

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[15]See Steve Baer, "Practical Solar Power: Steve Baer's Done'er Again," <u>The Mother Earth News</u>, XXVIII (July, 1974), p. 51, and S. Baer, "The Drum Wall," <u>Proceedings of the Solar Heating and Cooling for Buildings Workshop</u>, pp. 186-187.

Another idea that several people have proposed is the use of ponds on a building roof to collect and disperse heat.[16] A very water-proof roof is flooded with water or, using Ray Bliss' idea, large black plastic bags filled with water are laid on the roof. Moveable, insulated panels are placed over the pond (or bags) at night to prevent radiative or convective heat losses, and during sufficiently sunny weather the panels are removed so that the pond (or bags) are warmed by the sun. Conversely, the panels are left in place during the daytime in summer and removed at night to cool the house. Such a house has already been constructed in Phoenix, Arizona. Without any auxiliary mechanical heating or cooling and in temperatures ranging from subfreezing to 115°F, an interior temperature of from 68°F to 82°F was maintained.[17]

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[16] See for example H. R. Hay and J. I. Yellot, "A Naturally Air-Conditioned Building," Mechanical Engineering (January, 1970).

[17] H. R. Hay and J. I. Yellot, "A Naturally Air-Conditioned Building," Mechanical Engineering (January, 1970), p. 25. A post-script on Thomasen's house: His design of collector can also be used for cooling. During the cooling season, water is pumped to the collectors at night where it loses heat to the night sky just as in the last two designs we discussed. During the day the air-circulating system is operated to distribute the accumulated cool.

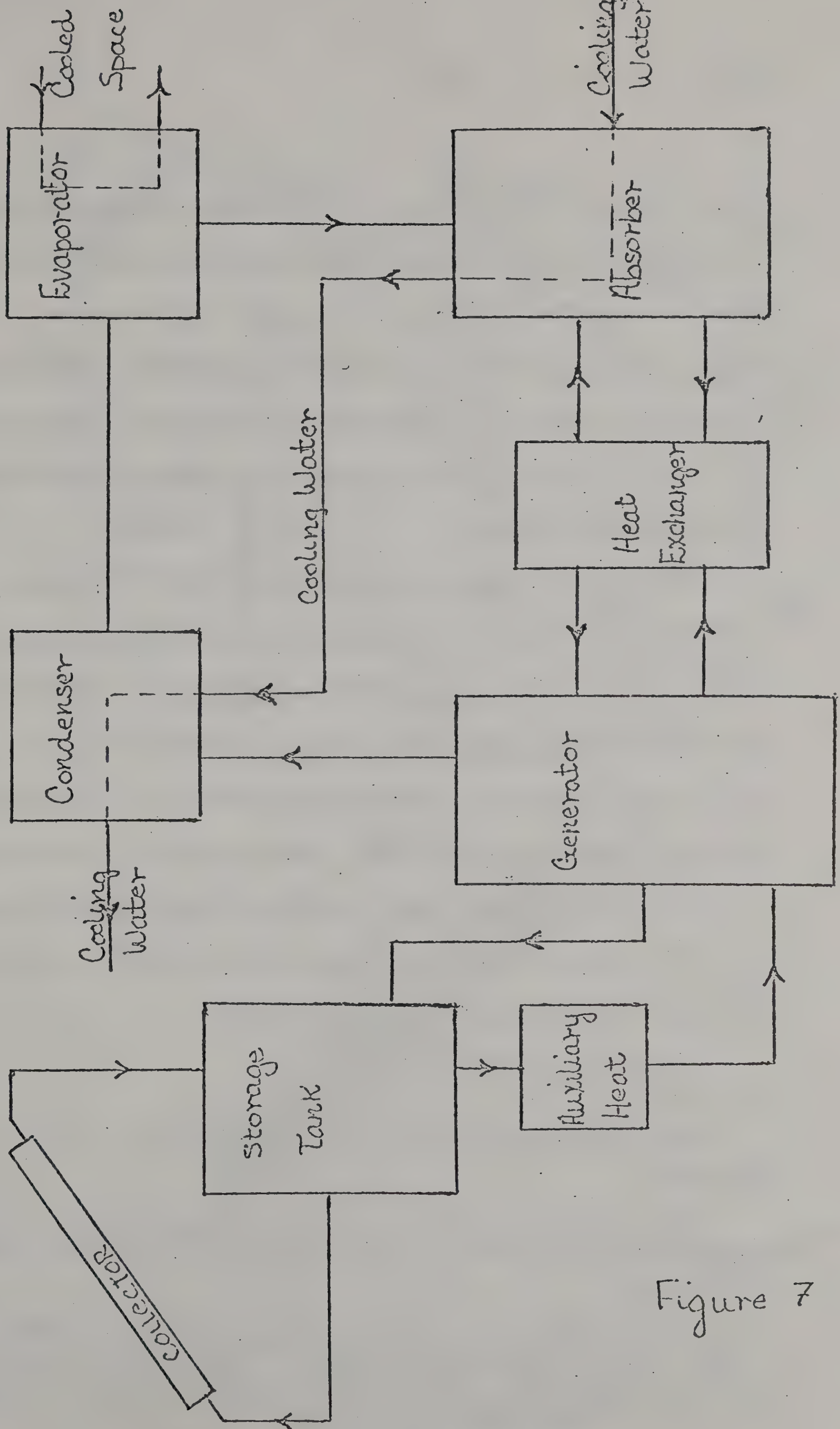
Cooled
Space
Cooling
Water
Evaporator
Absorber
Cooling Water
Heat
Exchanger
Condenser
Generator
Cooling
Water
Storage
Tank
Auxiliary
Heat
COLLECTOR

Figure 7

cannot happen simultaneously with the simple equipment employed. So a container of regenerated absorbent-refrigerant is put in the place to be cooled, cooling occurs, then the container is removed and the refrigerant distilled from the absorbent again, etc.[19] Because of its low cost, simplicity of operation, and intermittency, this type of cooling is more likely to be used in rural or less industrialized regions.

What sort of solar heating-cooling system is likely to be used in Montana? In figure 8 a schematic of a likely system is illustrated. Notice that <u>both</u> heating and cooling are included. It may have occured to you that the cost of energy from such a system will be less than for a system designed either for heating or for cooling. This is in fact true. Energy costs of less than $2.00 per 10^6 BTU can be realized using a combined system depending on location, collector area, storage capacity, etc.[21] But the systems don't necessarily have to be used together.

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[19] See R. K. Swartmann <u>et al</u> and others for a more complete discussion.

[20] W. R. Cherry and F. H. Morse, "Conclusions and Recommendations of the Solar Energy Panel," ASME Paper No. 72-WA/SOL-5 (November, 1972), p. 9.

[21] L. W. Butz, W. A. Beckman, and J. A. Duffie. "Simulation of a Solar Heating and Cooling System," (University of Wisconsin, Madison, Wisconsin). Compare this with natural gas at $2.97 per 1000 ft^3 or about $2.97 per 10^6 BTU.

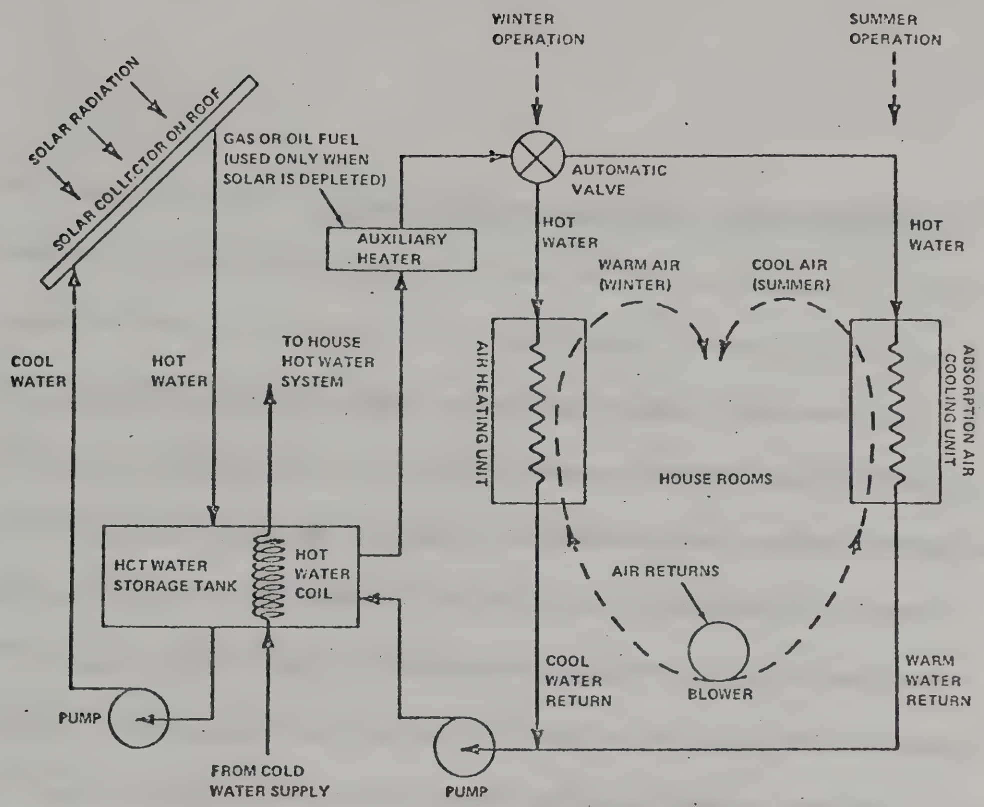

FIGURE 1 RESIDENTIAL HEATING AND COOLING WITH SOLAR ENERGY: SCHEMATIC DIAGRAM OF ONE ALTERNATIVE.

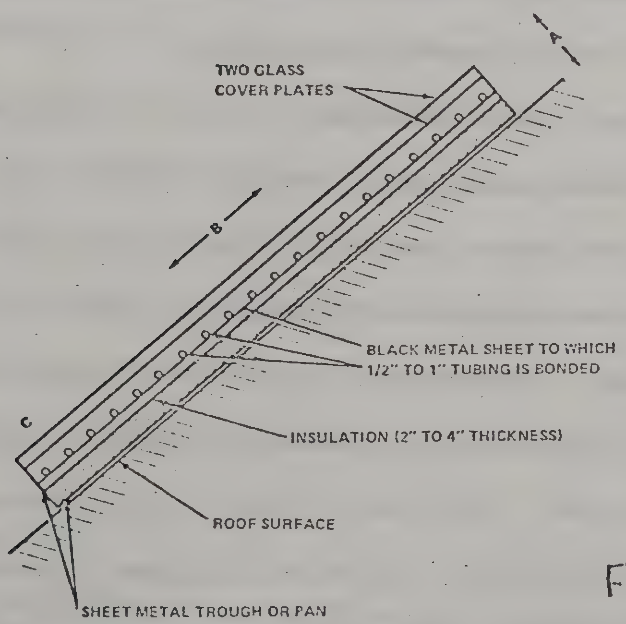

Figure 8[20]

NOTES: ENDS OF TUBES MANIFOLDED TOGETHER
ONE TO THREE GLASS COVERS DEPENDING ON CONDITIONS

DIMENSIONS: THICKNESS (A DIRECTION) 3 INCHES TO 6 INCHES
LENGTH (B DIRECTION) 4 FEET TO 20 FEET
WIDTH (C DIRECTION) 10 FEET TO 50 FEET
SLOPE DEPENDENT ON LOCATION AND ON WINTER-SUMMER LOAD COMPARISON

indirect use or control of solar energy

One aspect of utilizing or controlling solar energy that presently seems to be largely ignored in favor of mechanical heating and air conditioning is micro-climate control through the exploitation of trees and shrubbery and through the design of the house itself. Architects, contractors and sub-developers rarely seem to concern themselves with these natural methods of temperature control. Yet it is a relatively simple thing to do if the usual house design is modified or if attention is given to landscaping. Let's see what can be done to improve the situation.

First, what can be done to modify transform the usual cracker box with roof design into a more efficient house to heat and cool. Imagine two houses, one of the usual design and the other in the shape of a hemisphere. Furthermore, let's say that both have equal floor areas (since this is the way building space is usually specified) and also that both have equal insulation values and window areas. Now since the rate at which these shapes, kept at constant temperature, lose or gain heat depends solely on the volume to surface ratio, all other factors being equal, let's calculate the volume to surface ratio for each to see which is more favorable. The volume and surface of a hemisphere of radius R is $2/3\ \pi R^3$ and

$2\pi R^2$, respectively. Its floor area is πR^2. Specifying the floor area of the box-like house in terms of the hemisphere's radius and assuming the box to have its length equal to its width,[1] we have for the floor area πR^2 again and its length $\sqrt{\pi}\, R$ and width $\sqrt{\pi}\, R$. Let it be 8 feet high. Then its volume is $8\pi R^2$ and its surface exposed to the air is $32\sqrt{\pi}\, R + \pi R \cong 54R$. The volume-to-surface ratio (V:S) for the hemisphere is then R/3 and for the box it is about R/2. Recalling that the rate of heat loss or gain is a function only of V:S, all other factors being equal, and specifically that for a given volume of a constant temperature body, the larger its surface, the faster its rate of heat loss or gain, then we see that the box-like structure must gain and lose heat more quickly. So the ordinary house design is certainly not the most efficient in terms of temperature control and energy conservation. A geodesic dome is more efficient assuming that heat is distributed evenly throughout it. Actually, heat will not distribute evenly since heat will rise to its top unless there is mechanical circulation to prevent a temperature gradient between the top and bottom of the

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[1]Actually very few people build houses with this shape, but since this represents the maximum volume-to-surface ratio for this general geometry, we'll use it anyway. For a more realistic design, the ratio would be even more unfavorable.

dome. Even so, the design is worth considering given its superior ideal efficiency.

There are lots of ways to use naturally occuring convection currents to ventilate a house without resorting to mechanical means. A few of them are discussed and illustrated in The Owner-Built Home.[2] The savings in heating-cooling costs that could be realized by designing these relatively simple things into a house is difficult to calculate (so I won't even try)—better would be to actually measure these designs against the usual sort. One case in point, however: Wendell Thomas built a home so that air can circulate as in figure 2, and partially buried it in the ground.[3] Using only a small (how small isn't specified) wood heater, the interior temperature was from 60°F to 75°F the year round! Of course, western North Carolina, where he built his house, is not Montana, but the same principles will work in Montana to reduce heating and cooling costs.

Another simple but effective way to control heat gains is by planting deciduous trees that shade a house during the summer, but in the winter when the sun can help heat the house, the sun can shine

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[2]Ken Kern, The Owner-Built Home (Homestead Press, Aubrey, California, 1972), pp.

[3]Thomas, Wendell, "The Self-Heating, Self-Cooling House," The Mother Earth News, X, (July, 1971), p. 78.

Figure 1

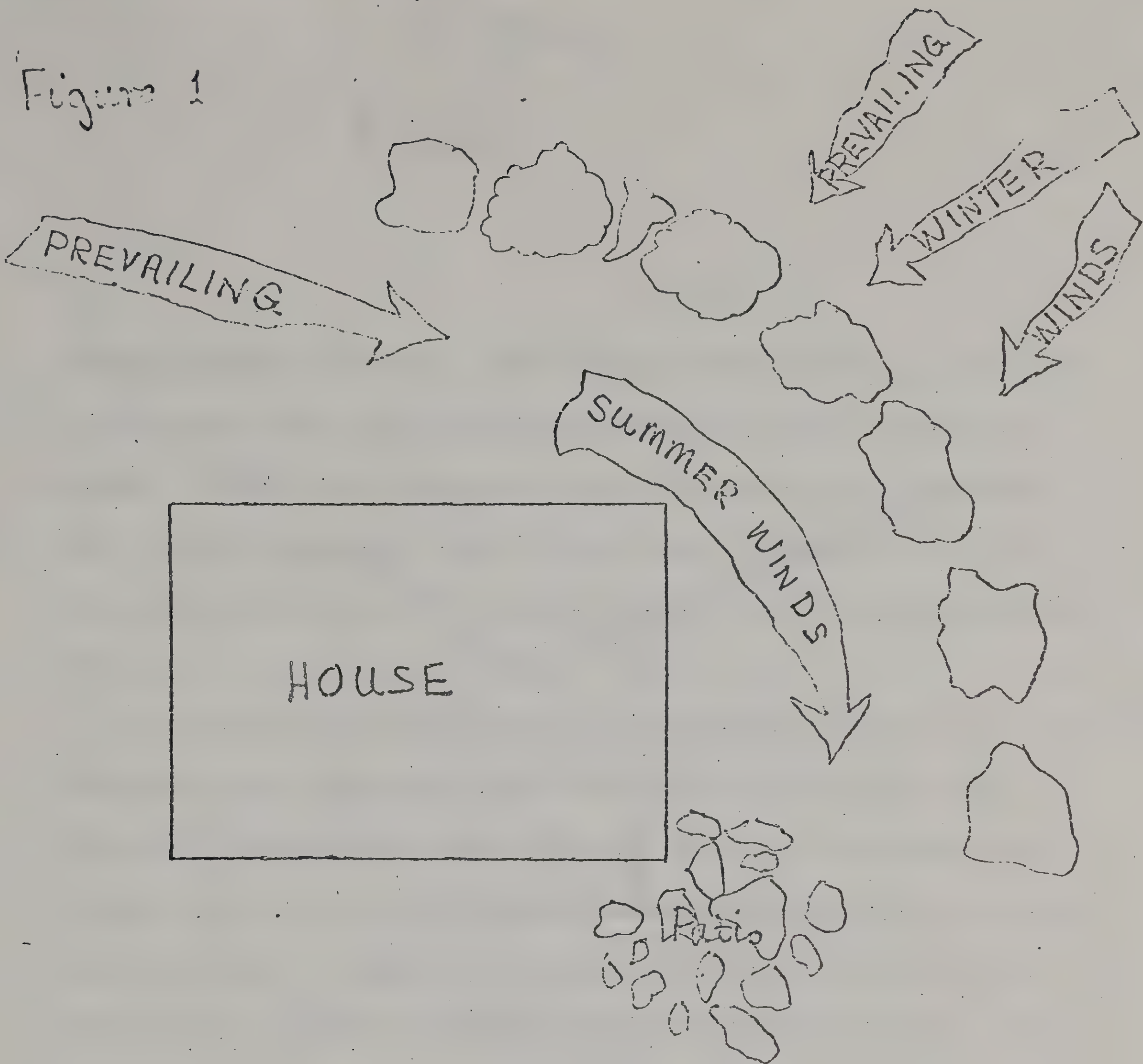


Figure 2

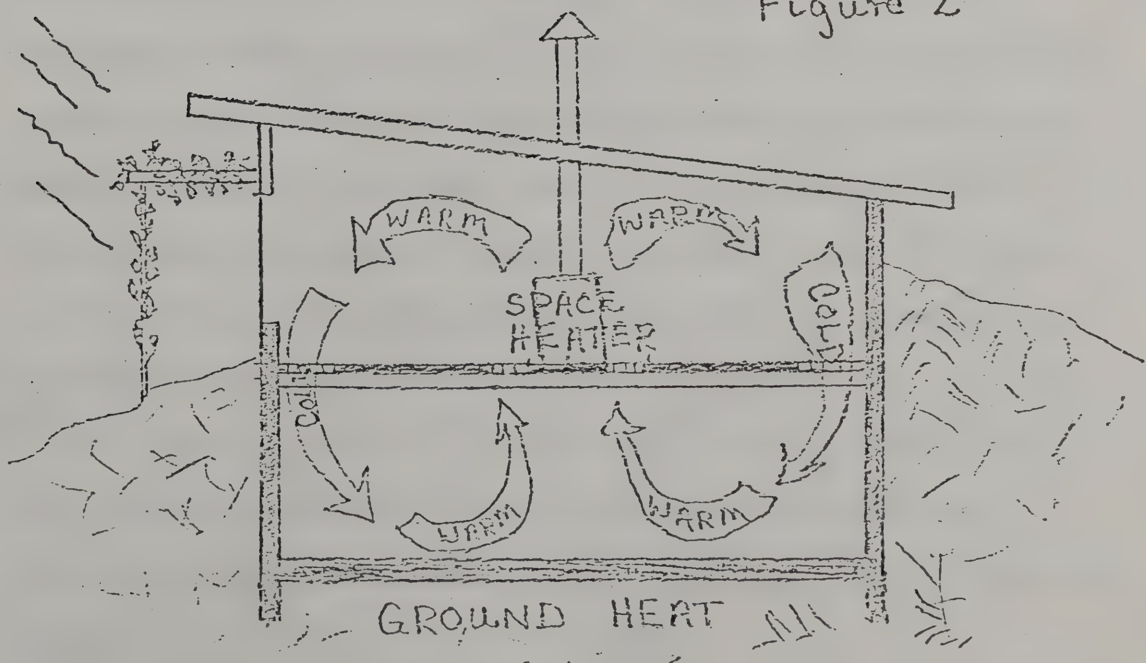
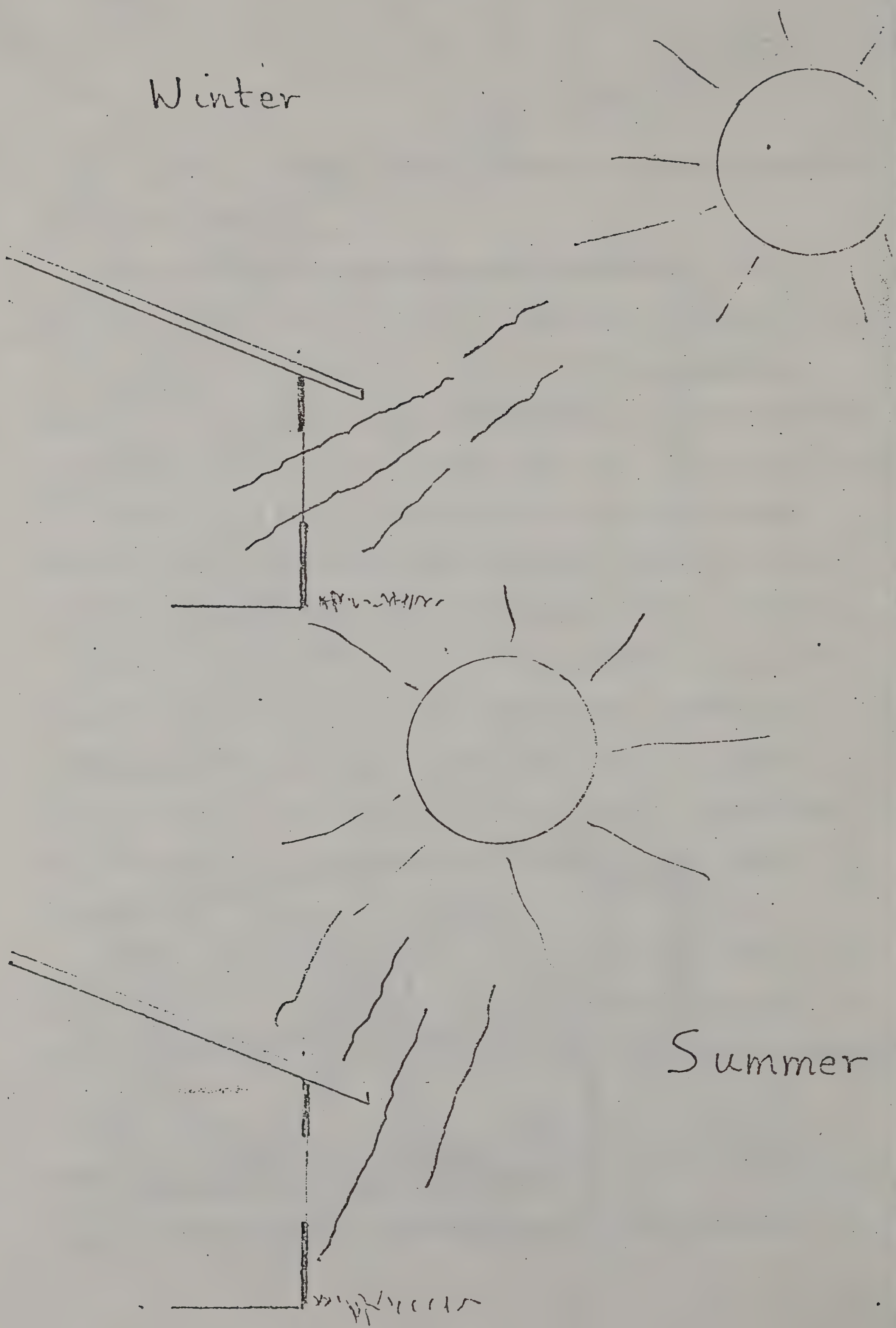


Figure 3.



through the bare branches. Using hedges and shrubbery can also help to reduce heating loadings in the winter and to cool the house in summer. Simply plant evergreen shrubs that block prevailing winter winds from the house but funnel summer winds around it (see figure 1). The cooling effects of wind are utilized in summer but averted during winter.

To control heat gains through a south-facing window, the use of awnings on large overhanging eaves is simple and effective (see figure 3). During the summer when heat gains are undesirable most of the time, the sun is blocked by the eaves or awning from entering a window, but in winter, when the sun is lower in the sky and the heat it can contribute is wanted, the sun shines through the window. To control heat losses from windows, the total area of windows in the house could be reduced or curtains can be hung in front of them to reduce radiative losses to the cold outdoor air. Large, easily removable sheets of insulation could be placed against a window to prevent heat losses, too. In fact, this can be quite an aid to conserve energy since single glass radiates heat at a rate of about 2 $kw/m^2{}^\circ C$ (1.13 $BTU/hr\ ft^2{}^\circ F$) and storm windows with 1 to 4 inches of space between them at a rate of 1 $kw/m^2{}^\circ C$ (.56 $BTU/hr\ ft^2{}^\circ F$).[3] Heat gain during summer could be reduced by using these same insulation panels or by using curtains and drapes with a reflective backing.

Now as one last exercise in reducing heat losses and gains in buildings, I'd like to show the relative worth of insulation for various fuel and insulation costs. Since heating seems to be more important in Montana than cooling, I'll only consider the effects of insulation for heating. Imagine two houses identical in every respect except one is insulated better than the other. The better insulated house has an overall insulation value of R-19 (.052 BTU/hr ft^2°F) and the other a value of R-11 (.091 BTU/hr ft^2°F).[4] If the area of the house exposed to the outside is A and the average annual number of degree days for a location in Montana is 8000,[5] then the first house loses 9984 A BTU and the more poorly insulated loses 17472 A BTU. If A is 2400 $feet^2$ (a small house, say 10'x20'x 50'), then the more poorly insulated house loses 1.773×10^7 BTU more heat than the first. Assuming a furnace efficiency of 75% and using natural gas at Bozeman prices, then over $20 in heating costs could be saved in one year by better insulation! That amounts to a cost savings of about 1¢/ft^2 of surface area. R-11 insulation is about

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[4] Insulation Manual: Homes, Apartments by NAHB Research Foundation, Inc. (Rockville, Maryland, 1971), p. 22.

[5] This is in fact about the normal number of annual degree days of heating for Bozeman. See reference 4 in the bibliography on energy conservation in houses.

11¢/ft^2 and R-19 insulation is 20¢/ft^2, a cost differential of 9¢/ft^2 (Bozeman prices). Thus, insulating a house to R-19 instead of R-11 could pay for itself in 10 years and then begin saving money in heating expenses.[6]

Lastly, let's consider personal savings resulting from using a clothesline instead of a gas or electric dryer. If you do clothes in a laundromat, say once every other week, and the dryer eats 30¢ (a fairly conservative figure) in dimes to dry your clothes, then in one year you can save yourself $7.80. Actually, this should probably be closer to $10 or more for a family wash. A clothesline could pay for itself in short order and at the same time help to conserve energy. The aesthetic difference between sun-dried clothes and machine-dried clothes may be worth the cost of a clothesline itself!

This far from exhausts the ways that the sun and wind can be indirectly controlled, particularly by wise architectural planning. For more ideas see reference 4. At least I hope that it is evident that there are many simple and ingenious ways to naturally reduce the mechanical heating and cooling load on a house.

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[6] This calculation should not be taken too literally as the effect of doors and windows was not considered. The individual house should be considered to get an accurate figure, but the calculation does establish the ultimate cost savings possible.

what there is in the wind besides air

Most people seem to be of the opinion that the wind is sort of a nuisance, tolerable only if it's light and you enjoy flying kites or sailing. Actually, these were two of the first ways the wind was put to use. Later came windmills of miscellaneous sizes and shapes, used for things as diverse as pumping water and grinding grain. Most people aren't familiar with wind-powered grist mills in this part of the country, but everyone has seen the many-bladed windmill still in use for pumping water. Probably quite a few have also seen, at one time or another, the three-bladed Jacobs wind charger that was widely marketed for the purpose of producing a modicum of electricity, especially in places that were remote from REA lines. The Jacobs machine was one of the most reliable and well-constructed wind generators ever sold. Its craftsmanship was peerless--many of them are still around and in serviceable condition 17 years after their production was stopped. They develop, on the average, 400 to 500 kwhr of electricity per month with a 15 foot diameter propeller and 10 to 20 mph winds.

Winds, as most everyone learns in a basic science class, are created by the sun's uneven heating of the earth (thus, they, too, are a kind of solar energy) and their direction governed by the

earth's rotation and local weather conditions. In this chapter I'd like to show that harnessing the wind is still a very practical idea. The energy that can be extracted from it is not only very reliable and predictable as we'll later see, but inexpensive, or at least it will be, and ecologically harmless. As I've mentioned before, the winds have 100 times more energy than the world presently consumes in a year. But a study[2] conducted in Oklahoma shows that it is even a more dilute form of energy than sunlight—199.13 watts m^{-2}. So the problem of getting energy in sizeable amounts from the wind appears at first glance to be even more difficult than getting it from the sun. The machines needed for extracting it aren't heat engines or solar collectors, however, so their efficiencies won't be limited by the laws of thermodynamics. Converting mechanical energy to electrical can be done quite efficiently—a 90% conversion efficiency is not hard to come by. In the case of windmills, efficiencies of 50%-80% are not difficult.

Wind generators, such as the Jacobs machine, are still on the market, ranging in size from 50 watts to 250 kilowatts output.

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[1] Marcellus L. Jacobs, "Experience with Jacobs Wind-Driven Electric Generating Plant, 1931-1957," Proceedings of the United Nations Conference on New Sources of Energy, Vol. 7 (New York, 1964), p. 337.

[2] Claude M. Summer, "The Conversion of Energy," Energy and Power. (San Francisco, 1971), p.103.

They all have one thing in common—the energy they produce is relatively expensive by U.S. standards.[3] Take for example a 2000-watt unit made by Quirks of Australia. Its undelivered cost, if bought from the U.S. retailer, is $2,790.[4] At 10% interest and a 5 year amortization period and somewhat pessimistically assuming only a 20 year life span plus an average windspeed of 10 mph which corresponds to about 120 kwhr per month output,[5] the electricity costs its owner about 13¢ per kwhr. Even by paying cash, a kwhr is still 9.7¢. If electricity is needed in a remote place with enough wind, the energy may be well worth the cost. In fact some Swiss hotels use wind-generated electricity. It should be noted that cost per kwhr goes down as the size of the unit goes up, at least if an optimum size isn't exceeded.

Examples of large and small, commercial or domestic wind generators are rife. Let me talk about just a few. The largest wind generator built to date was the Smith-Putnam installation on Grandpa's Knob near Rutland, Vermont. Its construction began early

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[3]Windmills for pumping water are still the cheapest way to get water however. But because their use isn't of extensive interest, I won't say anymore about them.

[4]Henry Clews. Electric Power from the Wind. (East Holden, Maine, 1973), p. 18. The 2000-watt unit includes storage batteries, tower and DC to AC inverter. The propeller diameter is 12 feet. Some have been in use in Australia for over 50 years.

[5]Ibid., p. 7.

in 1941 and the blades turned in August of that year for the first time. The two blades were 175 feet in diameter and turned at a constant speed of 28.7 rpm; the hub was 120 feet above the summit of the hill. The unit was rated at 1250 kilowatts (1.25 megawatts) in a 30 mph wind and withstood gusts of wind up to 115 mph. It operated until 1945 when one of its blades failed due to a structural flaw. During this time it produced electricity in 1100 hours of actual operation that was fed directly into the distribution system of the Central Vermont Service Corporation. The costs of this electricity aren't easy to estimate. The unit was only experimental, hence the actual amount of money spent on it is meaningless. However, Palmer Putnam estimated that a similar wind turbine, optimized in size, could generate electricity for .7¢ per kwhr (1945 costs) if at least 100 units were built.[6] Now there are better, more efficient designs for rotor blades so that structural difficulties should not be a problem, and also there is better generating equipment which would allow the machine to operate at a higher overall efficiency.

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[6] Palmer Putnam. Power from the Wind. (New York, 1948), p. 154. This is a good book to look at if you want to know more about the Smith-Putnam generator.

Joseph Tompkin recently estimated[7] that by using a system of 20 cyclone D-30 wind generators previously manufactured in Germany which were interconnected and located at Cascade Locks, Oregon, electricity could be made for .08¢ per kwhr (1951 dollars). The salient feature of this estimate is the interconnection of all generators. A unit by itself would produce energy costing .43¢ per kwhr. Now a few particulars about the Cyclone D-30: it is a three-bladed machine with a turbine diameter of 30 meters operating at a height of 50 meters. It maintains a constant blade tip velocity to wind speed ratio. It generates 720 kw in a 16 m sec^{-1} wind, or an average annual output of 2.125×10^6 kwhr in a 3.58 m sec^{-1} wind.

In Europe many wind generators have been built through the years, several of them commercial ventures. During World War II when fuel was difficult to get for the local generating plant on the island of Bogo, a wind power generator was built to produce DC power. In 1952 it was renovated with a 45 kw AC generator and a three-bladed 13.5 meter diameter turbine. From then until 1961 it was in continuous operation with only a minimum of maintenance done. The Danes also constructed another mill also with three blades, but larger--

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[7] Joseph Tompkin. "Introduction to Voight's Wind Power Plant," Wind Energy Conversion Systems: Workshop Proceedings. (Washington, D.C., 1973), p. 24.

24 meters in diameter. Its designed generating capacity is 200 kw in a 15 m sec^{-1} wind. It was put into continual operation from 1958 to 1961 without any major mishaps.[8]

There are many more wind generators turning out electricity, particularly in Europe where electricity is not so plentiful as here. To mention a few more: a 30 m, 100 kw DC wind turbine at Yalta (1931); a 20 kw generator near Berlin (1943); a 21 m, 130 kw installation for Electricité de France; a 24 m, 100 kw Enfield-Andreau wind-driven generator at St. Albans (1953); a 15 m, 100 kw John Brown wind turbine at Orkney, England; and a 35 m, 100 kw U. Hutter-Allgaier design in West Germany. I hope that by now it's obvious that wind power is technologically quite feasible. The only major difficulties in utilizing this technology are locating a suitable site and designing a mill for economic operation.

Finding a good location for a wind generator requires precise knowledge of the local wind regime. By local I mean not a general area, but the specific site at which the windmill is to be built. This entails measurement of the wind velocities on site—a task that has been done in only a very few instances. Wind velocities can

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[8]J. Juul. "Design of Wind Power Plants in Denmark," Proceedings of the United Nations Conference on New Sources of Energy, Vol. 7. (New York, 1964), p. 229-240. The last two windmills may still be in operation—the paper only reported on them until 1961.

vary over a wide range within a very short distance, so it is necessary to collect data in several places near the likely spot to determine the best location for the generator. Crests of hills faced with open country in the direction of the prevailing winds seem to be most often amenable to wind power (Grandpa's Knob is such a site). Likewise, coastal regions are favorable. But, as any flatlander can tell you, winds blow long enough and hard enough over the open country of the Great Plains so that to all appearances windmills could be built practically all across them.

Wind speed also varies with altitude. Near the ground, friction retards the wind so that its speed is less than what it is at a height of 50 meters. (Next time you're walking on a windy day, try laying on the ground to see how much slower the wind is at ground level.) This variation with altitude is a fairly obvious fact; but for all its conspicuousness, no one yet understands exactly how wind speed varies with altitude. Several specialists have attempted to empirically derive methods of predicting this variation--none have been completely successful. With the wind as with the sun, the most reliable procedure is measurement.[9]

[9]For more information on how the wind speed varies with altitude and with the type of terrain and also on site selection, see Putnam's Power from the Wind and several of the articles in Proceedings of the United Nations Conference on New Sources of Energy, Vol. 7.

Assuming that this sort of data is available, how can we tell how much power is in a wind? The power depends on three things: the area of the wind generator that is exposed to the wind, the windspeed and, of course, the overall efficiency of the machine itself. In table 1 I've compiled the amount of power contained in the wind for various wind speeds. (If you care to do it, look at appendix 4 to see how power is calculated.) There is a theorem, first derived by Betz, that says the maximum power derivable from <u>any</u> wind by <u>any</u> machine is 16/27 or 59.3% of the total power it contains. Thus, to calculate the amount of power that a specific machine can generate, we must find the total power the wind contains and multiply this by 59.3% times the overall efficiency of our wind generator. For a 100 m^2 turbine (corresponding to about a 5.6 m blade diameter) and a mechanical efficiency of 70%, we could get 2597.37 watts of power in a 5 m sec^{-1} wind or 166.04 watts in a 2 m sec^{-1} breeze. So we see that power is proportional to the wind speed cubed and the area of the rotor. Table 2 shows the maximum power a wind turbine, with a mechanical efficiency of 70%, could get for various turbine sizes. Figure 1 shows the power that generators operating at a 100% efficiency and a 70% efficiency produce.

In addition to the usual bladed turbine, there are a couple of other novel ways of harnessing the wind that ought to be mentioned. The Savonius rotor, illustrated in figure 2, is a particularly

Table 1

Wind Speed		Power
$m\ sec^{-1}$	mph	$watts\ m^{-2}$
1	2.2	.50
2	4.5	4.00
5	11.2	62.50
8	17.9	256.00
10	22.4	500.00
12	26.8	864.00
15	33.6	1,687.50
20	44.7	4,000.00
25	60.0	7,812.50
30	67.1	13,500.00
35	78.3	21,437.50

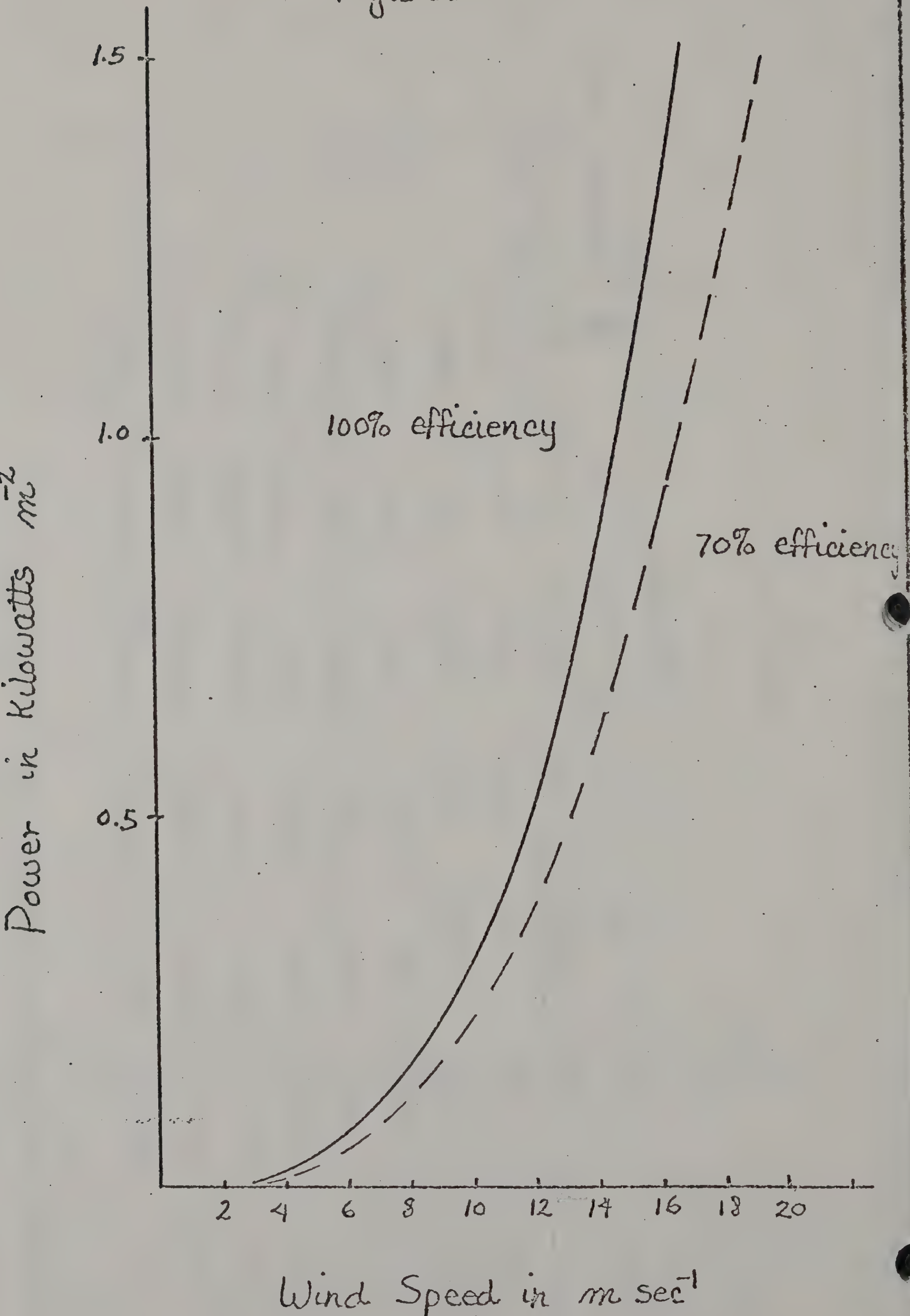
Power was calculated assuming an air density of 1000 gm m^{-3} (see appendix 4).

Table 2

Power (watts)		Rotor Size					
		1	2	5	10	15	20 : diameter (m)
		3.14	12.57	78.54	314.16	706.86	1256.64 : area (m^2)
Wind Speed ($m\ sec^{-1}$)	1	.65	2.60	16.30	65.21	146.4	260.7
	2	5.21	20.91	130.33	521.5	1174	2085
	5	81.65	326	2038	8184	18339	32602
	8	333.9	1336	8346	33384	75130	$1.33x10^5$
	10	652	2608	16301	65181	$1.47x10^5$	$2.60x10^5$
	15	2200	8802	54889	$2.20x10^5$	$4.94x10^5$	$8.8\ x10^5$
	20	5217	20865	$1.31x10^5$	$5.21x10^5$	$1.17x10^6$	$2.08x10^6$
	25	10188	40752	$2.55x10^5$	$1.02x10^6$	$2.29x10^6$	$4.07x10^6$

Here power is also calculated assuming an air density of 1000 gm m^{-3}.

Figure 1


1.5
1.0
0.5
Power in Kilowatts m^{-2}
100% efficiency
70% efficiency
2
4
6
8
10
12
14
16
18
20
Wind Speed in $m\ sec^{-1}$

simple device for generating electricity. Its application is not limited to electricity production though. It has been used to pump water for building ventilators and even to power ships. Its

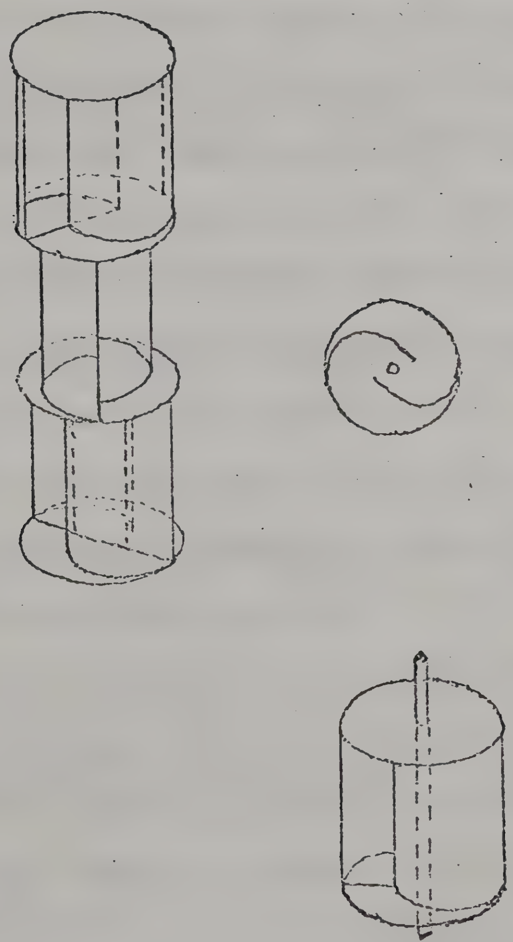


Figure 2

advantages over a horizontal axis wind generator are that it does not need to re-orient itself each time the wind changes direction

and also its low operational speed makes problems in balancing the rotor practically obsolete. Its low speed makes some sort of a pulley arrangement necessary if it is to be used for generating electricity, but it has more than enough torque to handle this with ease. The S-rotor is very simple to construct--most do-it-yourselfars should have no difficulty in constructing one out of old oil drums.[10] Its efficiency is somewhat lower than those attainable with horizontal axis generators, rarely exceeding 50%.[11]

A second unusual notion for putting the wind to work is that being studied by Ralph Powe and Harry Townes at Montana State University. They have been conducting a technical feasibility study on the possibility of building and successfully using a wind generator like that illustrated in figures 3 and 4. The airfoil supporting cars run on an oval track oriented so that its longest axis is perpendicular to the direction of the prevailing wind. The airfoils push the cars around the track much as the wind pushes a sailboat. Each car contains a generator driven by the wheels and whose output is fed through the tracks to a central distribution

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[10] See Michael Hackleman. "The Savonius Super Rotor" and "More About the S-Rotor" in The Mother Earth News for details of construction.

[11] This is mechanical efficiency meaning that roughly 30% of the total power in the wind can be captured by a Savonius rotor.

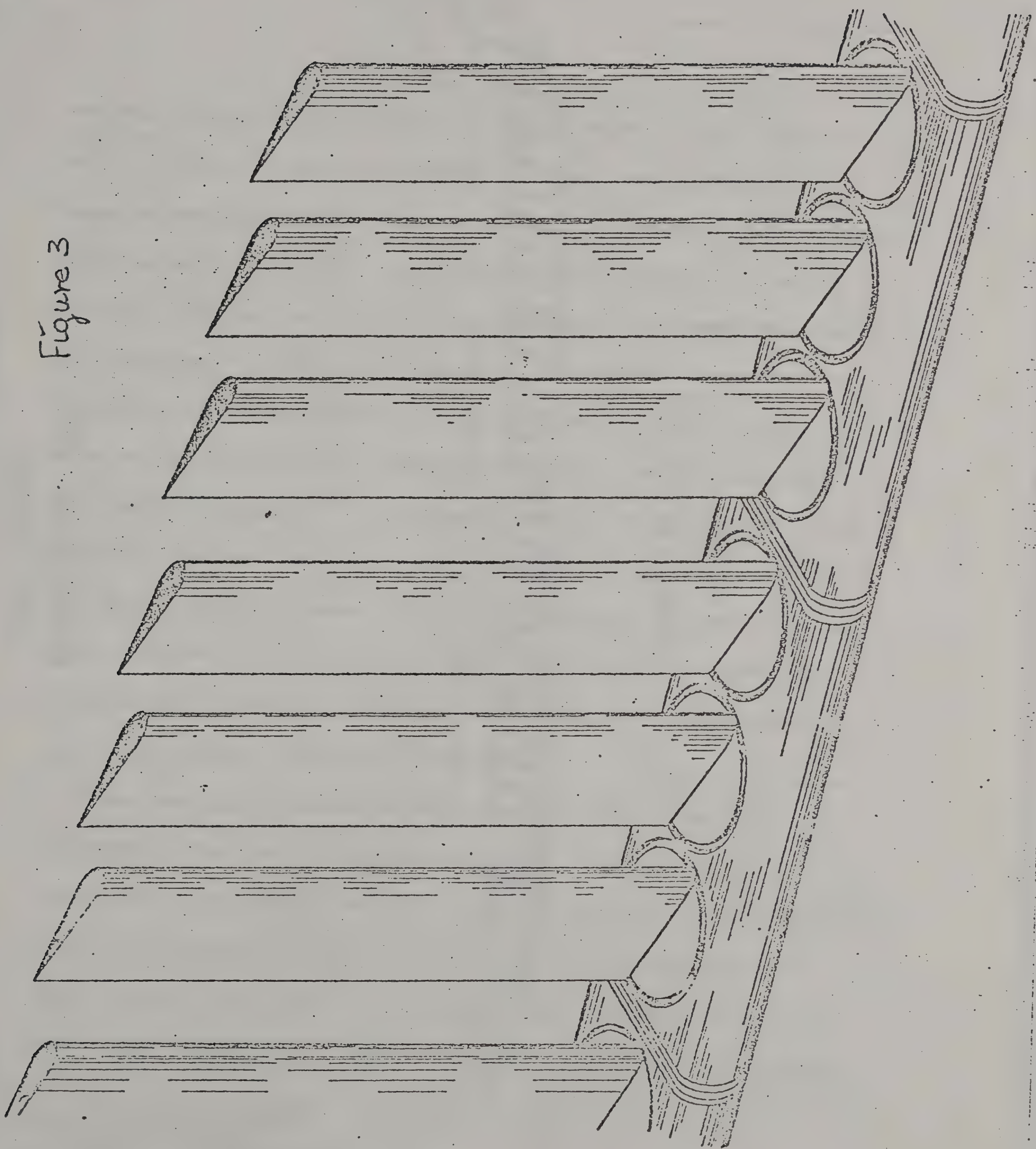
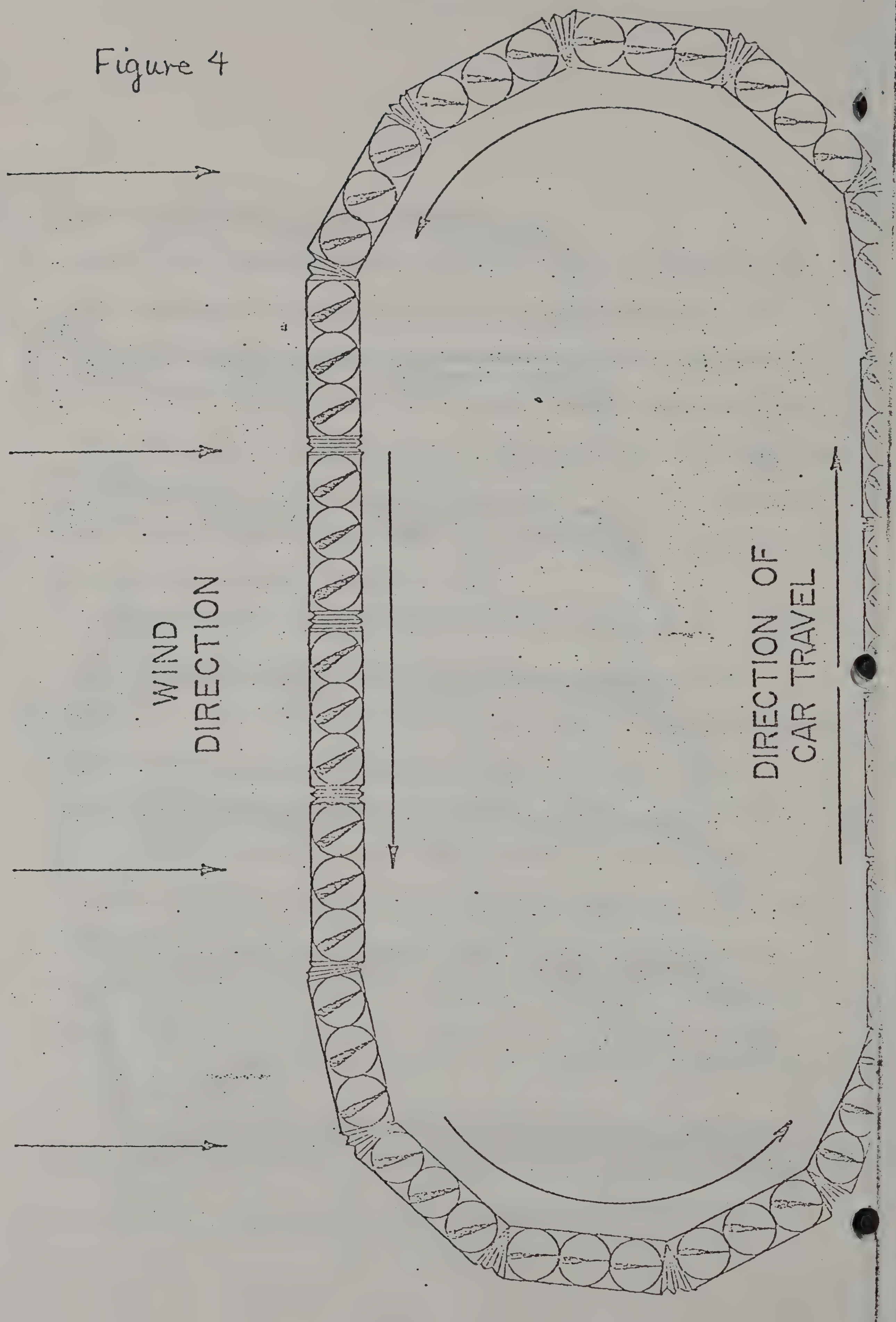


Figure 3

Figure 4



station. The airfoils are continuously adjusted so that they face the wind in such a way as to extract the most energy possible. Installations of megawatt size are dreamt of, operating with mechanical efficiencies of up to 80%. The power that can be gotten from the wind with this sort of an installation is strongly contingent upon the direction from which the wind hits it, the most favorable direction being perpendicular to the long axis. Hence, finding a place where wind direction remains essentially constant throughout the year is desirable.[12] An economic analysis of the system is now being carried out. An interesting addendum: a system of airfoils is also being used by a German ship building company to power an ocean-going freighter, which, it is claimed, will be able to cross the Atlantic with favorable conditions as quickly as an engine-powered ship and certainly much more inexpensively.

Now what about the utility of using any wind-harnessing apparatus in Montana? To get some idea of its practicality we must look at the wind speeds for various locations. As I've indicated before, wind-speed data are contingent on the exact location of measurements; only a short distance may make a major difference in wind speed and duration. But for a rough idea of favorable areas,

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[12] See Ralph Powe and Harry Townes. Technical Feasibility Study of a Wind Energy Conversion System Based on the Tracked Vehicle-Airfoil Concept. Figures 3 and 4 are from pp. 55 and 52 of this report.

the climatological data published by the U.S. Weather Bureau will suffice. In table 3 are mean wind speeds and standard deviations for the months of the year at sundry places in Montana.[13] In figure 5 is a frequency distribution of wind speeds over 25 years at Great Falls. Lastly, in table 4, the annual average wind speeds for each of these sundry places and the power contained in the wind as well as the extractable power at 100% mechanical efficiency and at 70% efficiency.

Now as a last exercise, let's see what this means in terms of total energy for one year. Imagine that we would like to put up a small wind generator with a 3 meter diameter propeller and a 70% mechanical efficiency. Then in one year at Great Falls we could extract 10562 kwhrs of energy[14]; for someone who builds his own

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[13]All averages are over 12 years except for Billings and Great Falls where the averages are for 21 years and 30 years respectively. An asterisk by an average indicates that one or more months of data were missing. The number below each average is the standard deviation which gives a rough idea of the predictability of the wind--the smaller the standard deviation relative to the average, the more likely the wind speed will be near the average.

[14]The overall mechanical efficiency depends on the size of the generator connected to the windmill (if electricity is the energy form wanted) and on the friction losses. The power generated isn't necessarily linearly related to windspeed, but most likely will be maximum at a given windspeed and less at speeds less or greater than this optimum. All these things must be considered before the energy output is blithely predicted.

Table 3

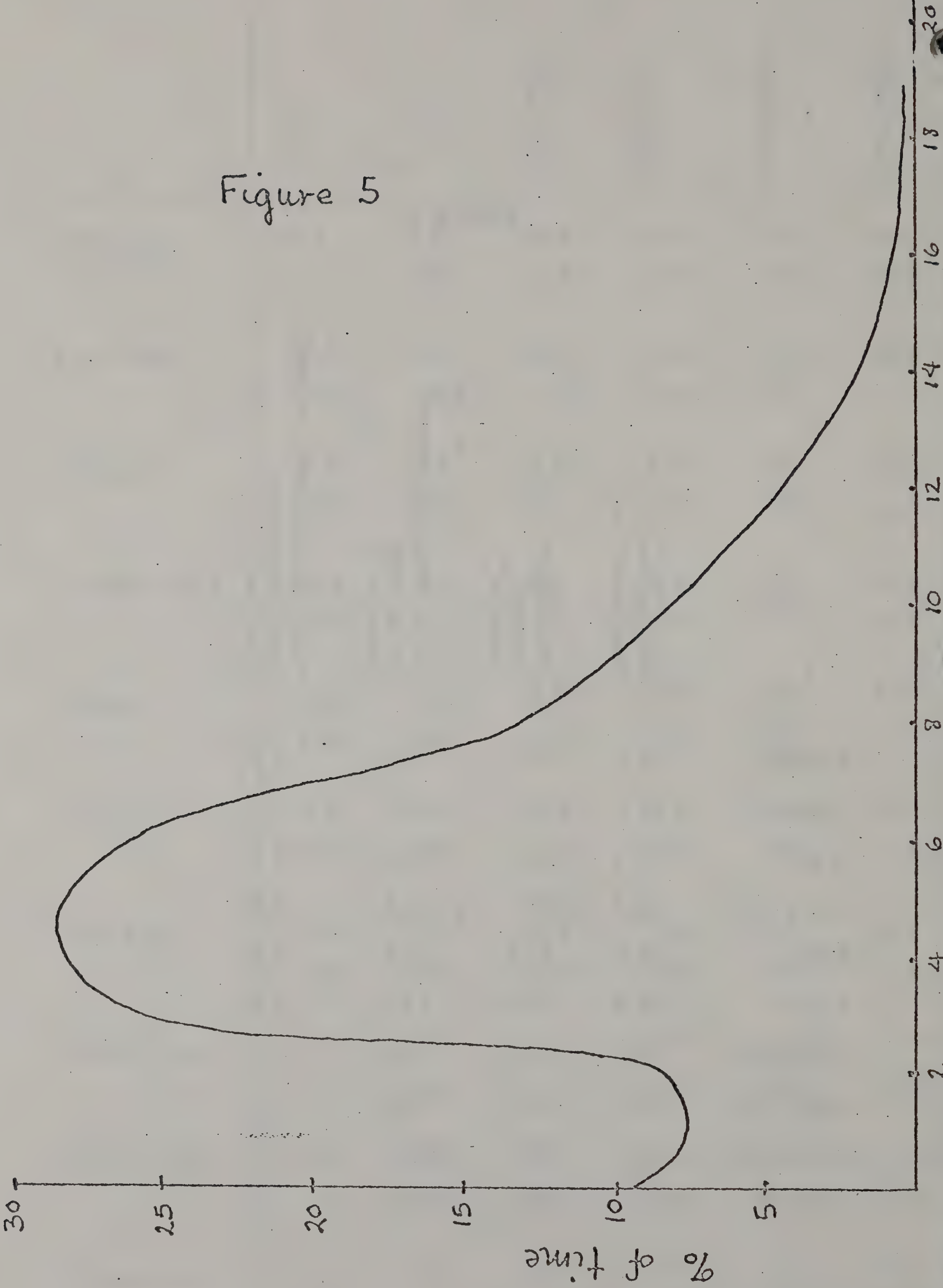
	January	February	March	April	May	June
Billings	13.2	12.6	11.6	12.0	11.2	10.6
	2.02	1.87	1.45	.91	.79	.94
Cut Bank	14.2	13.2	12.9	13.8	12.6*	12.0
	2.27	3.04	1.73	1.51	1.65	1.30
Dillon	10.6*	9.8	10.0	10.2	9.3	8.3*
	1.68	1.70	1.58	.82	.93	.38
Great Falls	15.6	14.9	13.4	13.3	11.8*	11.5
	3.45	3.25	3.05	2.03	1.83	2.00
Havre	10.9*	9.9*	10.0*	11.4*	10.7*	9.9*
	1.23	1.67	1.68	1.50	1.47	1.43
Helena	7.8	7.7	8.5	9.7	8.9	8.6
	.96	1.69	1.59	.83	.85	1.03
Kalispell	7.3*	6.2*	7.3	8.6*	7.8	7.2
	1.61	1.52	1.19	1.00	1.11	.91
Lewistown	11.5	10.7	10.4	11.1	10.5	9.3
	1.67	1.86	1.33	.94	1.89	.71
Miles City	9.8	9.5	10.4	11.6*	11.2	10.0
	1.57	2.16	1.33	1.55	1.58	1.11
Missoula	6.0	5.6	6.6	7.8	7.7	7.2
	1.26	.71	.72	.65	.49	.71

	July	August	September	October	November	December
[21] Billings	9.9	9.9	10.6	11.4	12.4	13.4
	.66	.59	.62	1.15	1.49	1.34
[12] Cut Bank	10.4	10.7	11.6	13.6	12.5	13.2
	.77	1.49	1.33	1.56	1.05	[illegible]
Dillon	7.8*	7.8*	8.6*	8.8*	8.8*	9.6*
	.83	.54	.80	.98	.96	1.35
[30] Great Falls	10.3	10.6	11.8	13.7	14.9	16.0
	1.61	1.30	1.80	1.92	2.99	3.48
Havre	9.3*	8.9*	9.7*	9.8*	9.6*	9.6*
	1.08	1.04	1.25	1.05	1.02	.69
Helena	7.8	7.5	7.8	7.4	7.1	7.0
	.66	.87	.74	.92	.66	.69
Kalispell	6.6	6.7*	6.8*	5.6	5.5	5.8
	.78	.70	1.04	.72	1.29	1.20
Lewistown	8.6	8.9	9.5	9.8	10.2*	10.7
	.79	1.10	.98	1.22	.96	.74
Miles City	9.5	9.5	9.9	10.0	9.2*	9.7
	1.22	1.06	1.39	1.52	1.55	1.14
Missoula	7.1	6.9	6.2	5.2	5.3	5.6
	.71	.78	.87	.79	.88	1.39

Table 4

	Average Yearly Wind Speed (mph)	Total Power in the Wind (watts m^{-2})	Total Extractable Power in the Wind (watts m^{-2})	Power Available to a Windmill of 70% Efficiency (watts m^{-2})
Billings	11.6	69.7	41.3	28.9
Cut Bank	12.6	89.3	53.0	37.1
Dillon	9.1	33.6	19.9	14.0
Great Falls	13.2	102.7	60.9	42.6
Havre	10.0	44.6	26.4	18.5
Helena	8.0	22.8	13.6	9.5
Kalispell	6.8	14.0	8.3	5.9
Lewistown	10.1	46.0	27.3	19.1
Miles City	10.0	44.6	26.4	18.5
Missoula	6.4	11.7	6.9	4.9

Figure 5



After Ralph Powe and Harry Townes.

wind generator that is not so efficient, say only 30% efficient, and with an area of 10 m^2, at Great Falls, 5336 kwhrs of energy could still be generated. Either way it is a substantial amount.

bio-gas

Strictly speaking, there seems to be little connection between the generation of methane and the accompanying fertilizer production by the anaerobic decomposition of organic materials and solar energy, but if a broad conception of solar energy is adopted, then this too is a form of solar energy even though it's a few times removed from direct use of the sun. Bio-gas and fertilizer production could be one of the very practical sources of alternative energy in Montana. Its development could be almost immediate, as we shall see, because the technology and skills needed to utilize it are minimal, requiring only someone with enough gumption to try it. And as fuel and fertilizer prices rise in the future, bio-gas plants will become increasingly attractive economically.

Just what is a bio-gas plant? Let me explain. There are two ways that all dead organic matter can decay, either aerobically (with oxygen) or anaerobically (without oxygen). In most peoples' experience, things decay aerobically simply because oxygen is omnipresent. Anaerobic decomposition typically occurs only under water, in swamps or marshes for example (hence, swamp gas and marsh gas). The difference between these two types of decomposition is mainly in the types of by-products and in the intermediate stages lying

between the inception of decay and its end when only the decay by-products and humus remain. Aerobic decomposition, of which a compost pile is an example of its control yields such by-products as carbon dioxide, nitrogen compounds and some other gases in lesser quantities plus lots of heat. Of course, there is plenty of rich organic matter to add to the earth in the end. Anaerobic decay, on the other hand, produces methane, CO_2, hydrogen sulfide and some other gases but not much heat. Both processes destroy bacteria harmful to animals so that the humus may be safely used in agricultural applications.

The gases from anaerobic decay are useful for energy whereas those from aerobic decomposition contain nothing flammable. Typically bio-gas, as I shall now call the gas from anaerobic decomposition, consists of about 60% methane and 30% CO_2 with the remainder divided among the trace gases. Also the solid materials are richer in nitrogen-containing compounds (ammonium) than those from a compost pile which have oxidized nitrogen compounds (nitrates, nitrites). Thus, if anaerobic decay could be successfully controlled like composting controls aerobic decay, a new source of energy plus ammonium-rich fertilizer would be available.

But is it possible to economically build a bio-gas plant that will do all these things? Certainly the capital investment will have to be larger than that involved in a compost pile since it is

no easy matter to keep oxygen away from anything (unless it happens to be amphibious). Historically it has in fact been done at various times and places. During World War II several different types of bio-gas plants were developed in Germany for use on farms because of the shortage of conventional fuels for private and domestic uses. They were employed quite successfully by farmers with anywhere from 25-300 cattle, or their manure-producing equivalent in chickens, hogs, horses, etc., and produced gas for cooking, tractor fuel, generating electricity and for heating the bio-gas plant itself. Bio-gas plants were also used before 1945 (and, in some instances, are still used today) in Algeria, France, Italy and India.

Well, then, what's happened to bio-gas plants after 1945? Their design and development, until recently, seems to have been limited to the work of Ram Bux Singh and his colleagues in India and to L. John Fry who independently and single-handedly developed a bio-gas plant for his 1000-hog farm.

In India, the expense of fuel for any purpose and the difficulty in acquiring it even with the necessary money lead the Indian government to finance a project with the aim of developing a low-cost way of producing bio-gas and fertilizer for individual villages and for individual farmers. It has resulted in the design of at least seven different kinds of bio-gas plants, each one simple enough for nearly anyone to construct and cheap enough so that almost anyone

or any village can do it. Several of these plants have been constructed in India, and with modification, there is no reason that the same designs could not work in Montana. The plants have capacities ranging from gas production of 100 ft^3 to 2500 ft^3 daily. There is no technical objection for not making them larger however.

In fact, L. John Fry has built a larger one on a pig farm in South Africa, one that produces from an average of 8000 ft^3 to a maximum of 12,000 ft^3 of bio-gas daily. His experience with bio-gas began when he realized that his time was being consumed by disposing of about two tons of hog manure a day. He at first composted it, but the process was labor consuming. Finally, after some initial research and experimenting, he designed and built a bio-gas plant. Some of the gas that was produced he used to run converted diesel engines which pumped water and generated electricity for 6 years—continuously! The heat from the engines was re-cycled, used to keep the bio-gas plant at its optimum temperature.

The bio-gas plant initially cost him $10,000 including his diesel power plant. Figuring the thermal value of the bio-gas to be 585 BTU/ft^3 at the altitude of his farm, about $7.57 of gas was produced daily for a total value of $16,578 in the 6 years that he operated his farm (1973 dollars). And this is the value of the gas alone--it does not include the increased value of the manure as

fertilizer or the labor saved as a result of its installation. His experiment with bio-gas plants is impressive by any standard.[1]

Some words on the conditions under which anaerobic decomposition proceeds are in order. There are four major factors affecting anaerobic digestion: acidity, temperature, carbon-nitrogen ratio and the percentage of solids. Oxygen if, of course, a major factor affecting it, but air must simply be rigorously excluded from contact with the material to be decomposed. The anaerobic bacteria responsible for the decomposition of the materials into methane, etc., are killed by exposure to oxygen. Let me discuss each of the remaining factors separately.

These particular anaerobic bacteria are temperature sensitive. They live and reproduce in temperatures ranging from 32°F to 156°F. One type thrives from 120°F to 140°F and another different kind lives best in a temperature range of from 85°F to 105°F. Luckily, the bacteria living in the lower temperature are hardiest and least sensitive to temperature fluctuations. Hereafter, I will talk only about the bacteria living on the lower temperature range. The speed of decomposition and the speed of bio-gas production is sensitive to

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[1] L. John Fry and Richard Merrell. Methane Digesters for Fuel Gas and Fertilizer. (Pescadero, California, 1973), pp. 40-44.

the temperature at which the methane bacteria live,[2] the most favorable temperature being 95°F. (See figures 1, 2 and 3.) Thus, in order to produce gas most quickly and to complete decomposition most rapidly, the organic matter being decomposed ought to be maintained at a temperature of about 95°F (a range of from 80°F to 100°F is actually satisfactory).

The acidity of the material decomposing is also important. During the acid-producing stages of decomposition, the pH of the material is about 6, but when the methane-producing bacteria take over, the pH rises to between 7.5 and 8.5 and stays there until decomposition is complete. At the time when the pH is at this level, the mixture of decomposing material is buffered, and additional amounts of material may be added for decomposition without substantially affecting the process because the mixture will maintain or adjust its pH so that it remains near the optimum value. So the pile of anaerobically decaying material can be supplied with fresh stuff, and the gas production can be continuous rather than cyclic.

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[2]There are two kinds of bacteria responsible for the type of anaerobic decomposition in which we're interested. In the initial stages of decomposition, the organic materials are broken down into volatile acids by acid forming bacteria. These acid bacteria are not very sensitive to changes in their environment. But the methane bacteria, those which convert the volatile acids into methane gas, are very sensitive to environmental changes; hence, when I speak of factors affecting rates of decomposition, I mean those things which affect these particular bacteria.

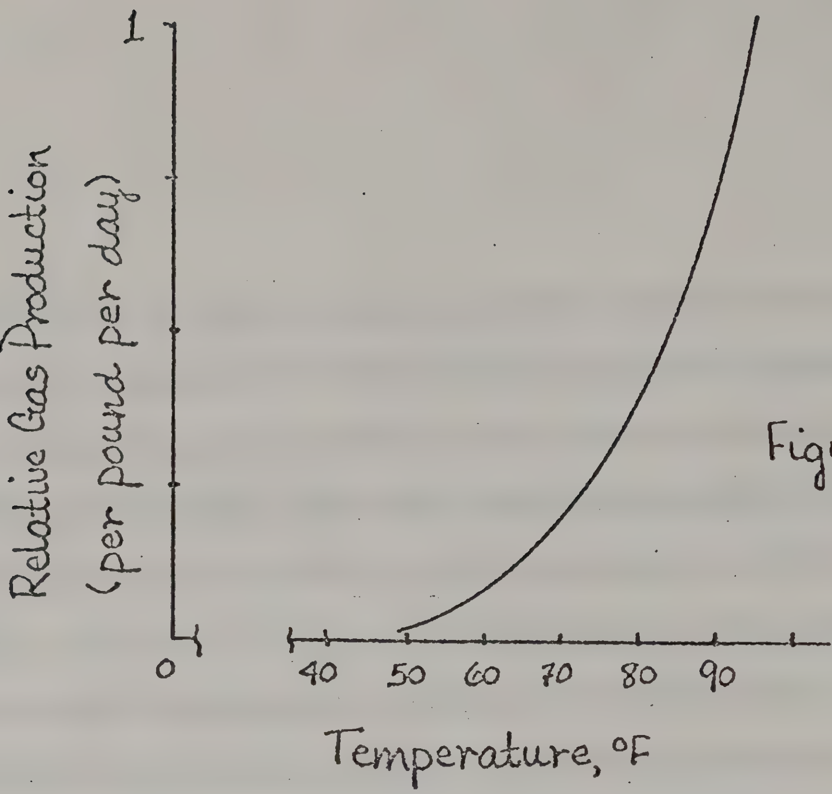


Figure 1[3]

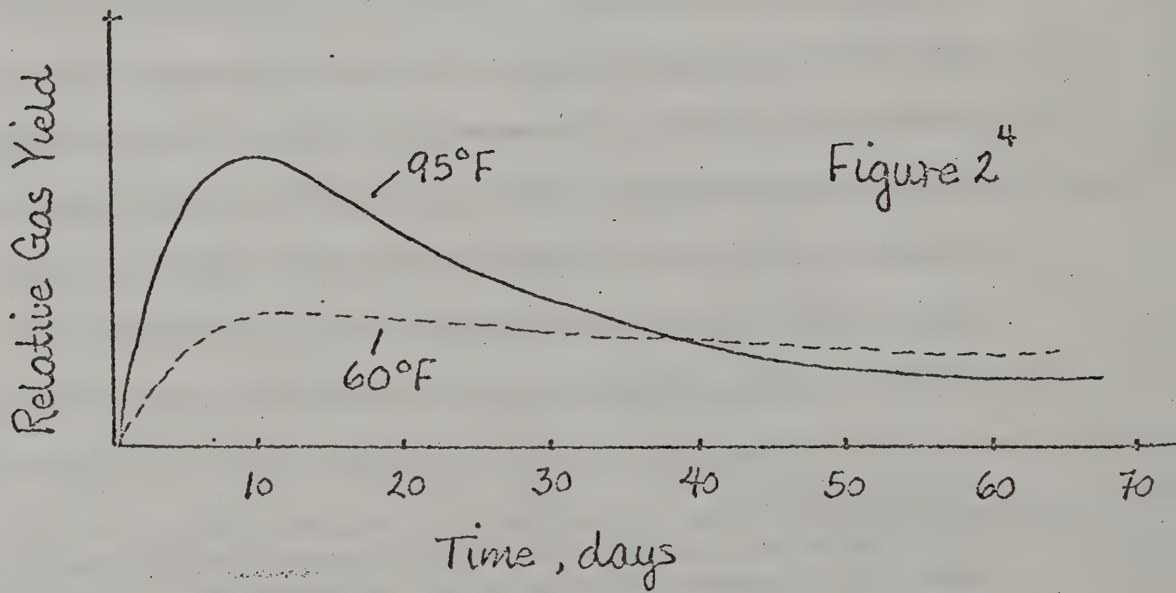
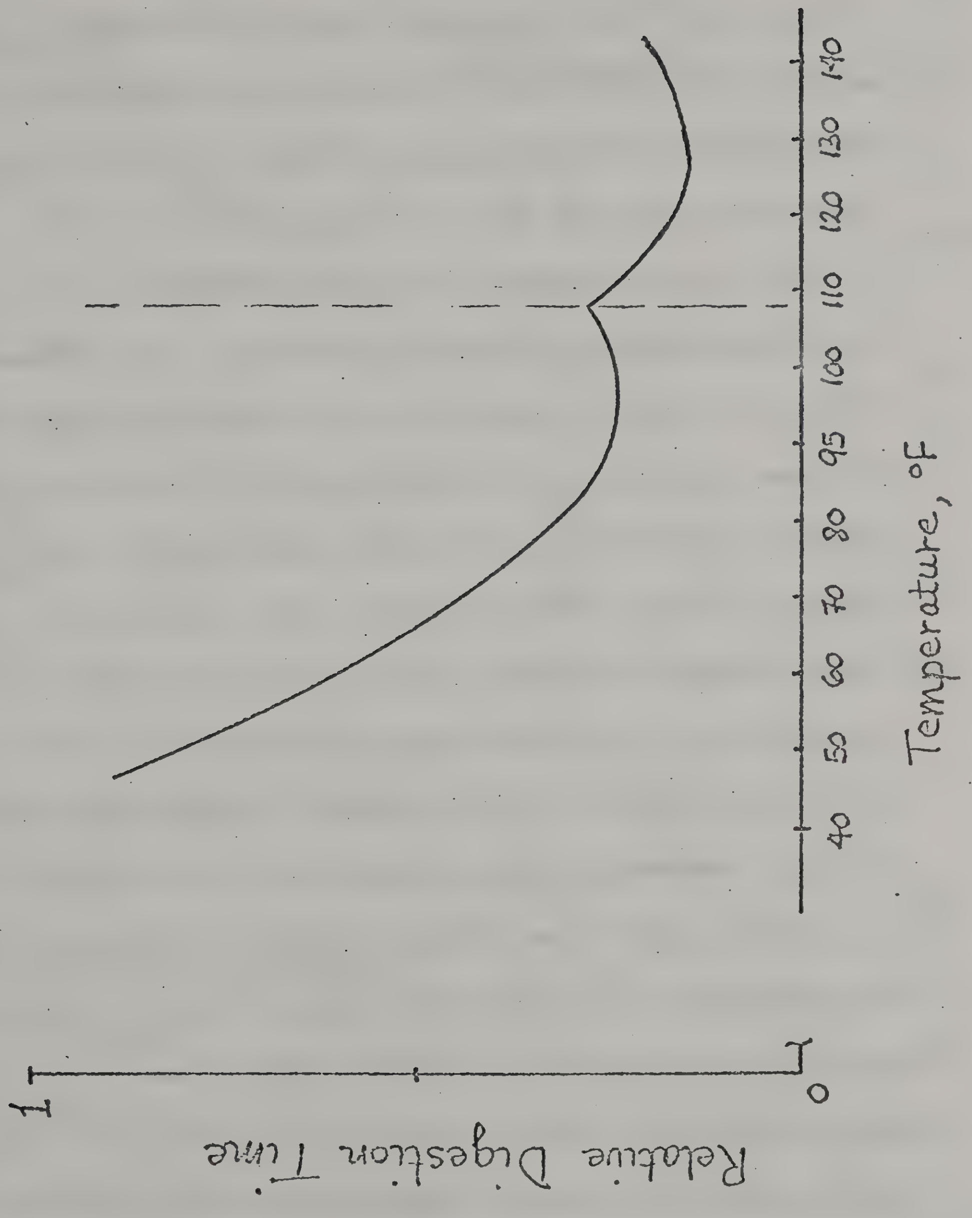


Figure 2[4]

[3]After L. John Fry and Richard Merrill, Methane Digesters for Fuel Gas and Fertilizer, p. 11.

[4]Ibid.

Figure 3[5]



[5] After L. John Fry and Richard Merrill, <u>Methane Digesters for Fuel Gas and Fertilizer</u>, p. 10.

(If only one batch of material was to be decomposed, then, at the optimum temperature, gas production and decomposition would be substantially complete in about 50 days. This time also depends on the type of material and its concentration.)

The ratio of carbon to nitrogen in the material to be anaerobically decomposed is also very important. The optimum ratio is 30-35 to 1, that is, 30 to 35 parts carbon for every part nitrogen. With too much carbon, the fermentation process exhausts the nitrogen and some carbon remains with the consequence of slowing the entire process. If the ratio is too low, then the carbon is exhausted first, fermentation stops and the remaining nitrogen is lost as ammonia gas. The ultimate consequence of a low carbon-nitrogen ratio is a reduction of the nitrogen content of the decomposed material rendering it less valuable as a fertilizer.

So the percentages of both carbon and nitrogen in the original material must be estimated or measured. Actually this task is not nearly so difficult as it sounds. If only manure is to be used for the fermentation process, then by simply mixing it with water until it has the consistency of cream, a satisfactory material is gotten. But if the carbon-nitrogen ratio must be estimated, references 1 or 2 give tables by which it can be guessed at for various materials. (See table 1.) According to both Mr. Fry and Mr. Singh, after a bit of experience with a bio-gas plant, a mixture of materials that will produce optimum gas production can be eyeballed.

Table 1[6]

Manure	Total Nitrogen, % of dry weight	C/N Ratio
Human, feces	6	6-10
urine	18	
Chicken	6.3	15
Sheep	3.8	—
Pig	3.8	—
Horse	2.3	25*
Cow	1.7	18*
Plant Wastes		
Alfalfa	2.8	17*
Non-legume vegetables	2.5-4	11-19
Oat straw	1.1	48
Wheat straw	0.5	150
Sawdust	0.1	200-500

*Nitrogen is total dry weight nitrogen and carbon is either total carbon (dry weight) or (*) non-lignin carbon.

[6] After L. John Fry and Richard Merrill in Methane for Fuel Gas and Fertilizer. (Pescadero, California, 1973), p. 16.

That leaves one last important variable to be controlled--the concentration of solids in the mixture to be decomposed. Ideally this mixture will have about 9% solid in water solution--a slurry with a cream-like texture. Either too great or too small a concentration of solids inhibits efficient digestion.

Four parameters plus the exclusion of oxygen from the slurry--it's beginning to sound like a high-technology project! But construction of a bio-gas plant is really quite simple as anyone looking at any of the first three references can see. Basically, a bio-gas plant consists of a tank (or tanks) in which the slurry of decomposible materials is held, a way of adding more material and removing completely decomposed material and a way of removing the bio-gas that is generated. The central tank and associated paraphenalia is called a digestor.

Digestors are classified into four categories according to whether they are batch or continuous feed types and according to whether they are vertical or displacement types. Batch type digestors are loaded with material, sealed and left alone until the process of digestion is complete—anywhere from 50 days to 90 days depending on temperature and the other important variables. They have advantages over other types of digestors in that they require little, if any, daily attention. But the disadvantage of batch digestors is that they do not produce a continuous and even flow of

gas since the gas production of the digestor peaks at some time during the period required for complete digestion and then tapers off. This can be solved by using more than one digestor and loading them at different times.

Continuous feed digestors, useful where the supply of digestible materials remains fairly uniform, are fed materials at regular intervals and have digested slurry removed from them at the same time. So, on a chicken farm, feed-lot or dairy farm, material could be dumped into the digestor daily. Gas production, after an initial start up period, is continuous and, depending on how closely temperature is regulated and upon the uniformity of materials, is also produced at a fairly even rate.

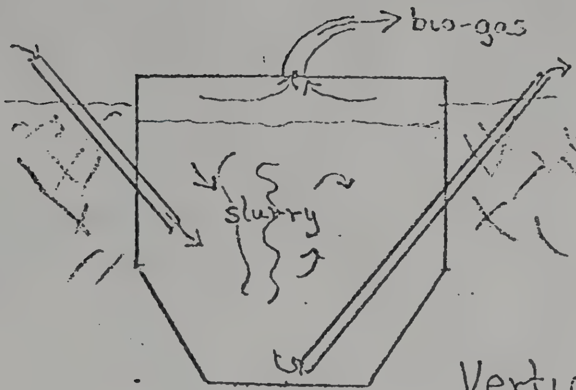
The other two classifications of a digestor into vertical or displacement types simply refers to whether the digestor is horizontal or vertical. Most digestors built have been vertical types, consisting of an upright cylinder usually buried at least partially in the ground so that feeding it is a simple matter. The gas collection on this type of digestor is also quite simple. Either the top of the cylinder is sealed tightly and the bio-gas allowed to flow from the top of the slurry to a place for storage or use, or it is another cylinder, with one end open and of a smaller diameter than the main digestor tank, inverted over the slurry in

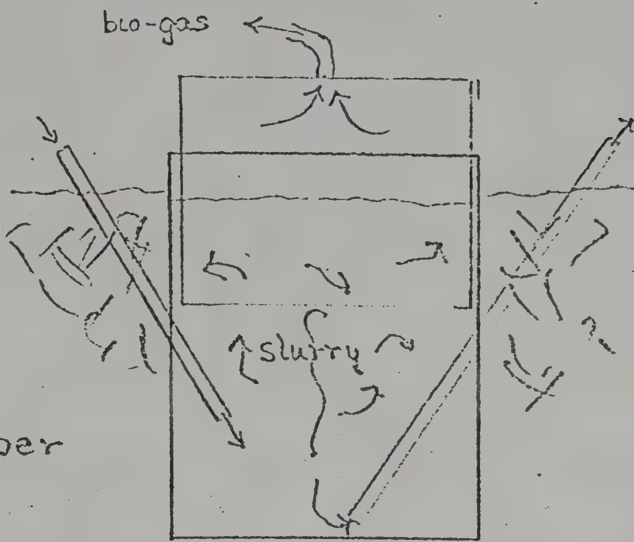
the main tank to catch the gas. As the gas accumulates in this inverted cylinder, it rises. The gas can be drawn off through a valve at the top for use having the advantage that it is slightly pressurized from the weight of the inverted cylinder (see figure 4).

The displacement digestor is a horizontal cylinder. The materials to be digested are dumped into one end, and as the process of fermentation progresses, move toward the opposite end of the cylinder. This digestor geometry possesses an advantage over the vertical type in that the vertical digestor tends to have its surface clogged with straw after some time, whereas the problem is reduced in the displacement type.

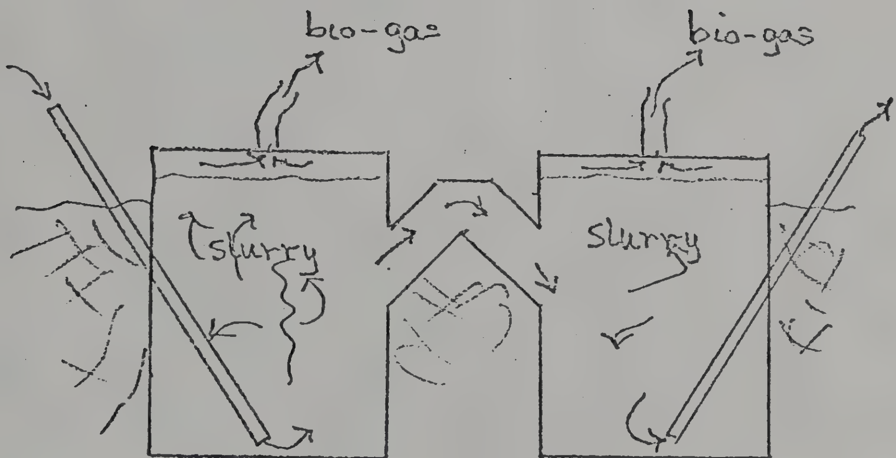
Vertical digestors may also be built in one or two stages. Since digestion of materials does not progress at a uniform rate but tends to produce the maximum amount of gas in the first 2/3 of the total digestion time, it may be desirable to build a digestor in two parts: the first stage for the maximum production of gas and the second stage for completion of digestion. The relative sizes of the two stages must be calculated from the portion of digestion that should occur in each. For example, if 2/3 of the digestion is to be done in the first stage and it takes 20 days to complete this while total digestion takes 50 days, then the ratio of sizes of the first to the second stage must be 2/3.

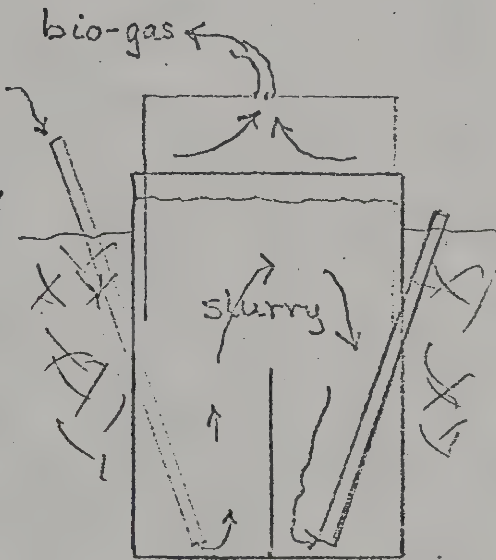
Continuous Feed Digesters



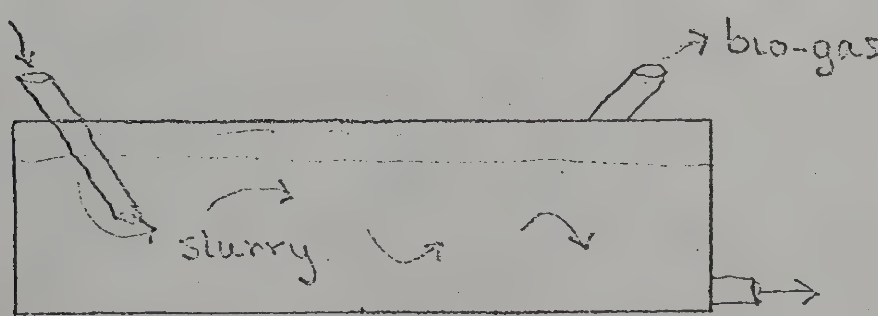


Vertical Single Chamber Digesters





Vertical Double Chamber Digesters



Horizontal Displacement Digester

Figure 4

There remains a few loose ends to tie up. Assuming that someone wants to build a bio-gas plant, how large should it be built, how much gas will it produce and most importantly, how much will it cost? The answer to the first loose end is relatively easy--its size depends on the volume of manure and/or digestible materials available to feed it and on the digestion time required for these materials. But in the individual case this may not be so easy to establish. First, note that not only is manure digestible, but nearly any organic material found on a farm lends itself to anaerobic decomposition. In fact plant material produces about 7 times as much bio-gas as manure pound-for-pound. The total amount of gas produced depends on what the animals making the manure are fed (grain-fed animals make better manure for methane plants), and the composition of the slurry fed into a digestor. The gas from plant decomposition usually has a higher CO_2 content and, therefore, a lower BTU/ft^3 value. Plant material, under near optimum conditions for digestion, takes about 70 days to digest while manure takes about 50 days. But some mixture of plants and manure will probably produce the optimum carbon-nitrogen ratio for digestion. Now once the optimum mixture and daily (or weekly, monthly, yearly) availability by volume is established and digestion time is roughly determined, then the capacity of the digestor is daily volume times digestion time

for continuous feed digestors. In the case of batch digestors, capacity is determined by the amount of material available at the time of loading.

But enough of this. It isn't my intention to give a do-it-yourself set of plans for a methane generator. For this you must consult some of the references cited in the bibliography, in particular Ram Bux Singh's book or better, L. John Fry's tome, Practical Building of Methane Power Plants. But I would like to do a cursory analysis of the economics involved.

In Ram Bux Singh's book (reference 11) is a list of the costs for constructing methane generators of various sizes which Mr. Singh and his colleagues designed for ease of construction, ease of maintenance and for their economical construction. The costs of construction in the U.S. were estimated in 1971. In table 2 I've reproduced part of his table and added some additional figures. These plants are small capacity compared to L. John Fry's 8000 ft^3 per day plant—needless to say, the costs of the methane gas will be reduced even farther for a bigger plant (see the case history of L. John Fry's plant earlier in this section).

These methane digestors could have a use in Montana. Feed lot operators ought to be particularly interested in them because they offer a way to profit from an otherwise bothersome problem. Manure from the lot could easily be fed into a large digestor (such as

Table 2

Size of Bio-gas Plant in ft^3 of Gas Produced Daily	Initial Cost	Total Cost[8]	Kilowatt-Hours of Energy per Year[9]	Value of the Bio-gas per Year[10]	Cost of the Bio-gas per Kilowatt-Hour[11]
100	$ 400	$ 527.60	3480.84	$ 69.62	$0.00152
250	900	1,187.10	8702.1	174.04	0.00136
500	1,800	2,374.20	17404.2	348.08	0.00136
1250	4,000	5,276.00	4.351×10^4	870.20	0.00121
2000	5,500	7,254.50	6.962×10^4	1,392.40	0.00104
8000[12]	15,000	19,784.81	2.785×10^5	5,570.00	0.00071

[7] Singh, Bio-gas Plant: Generating Methane from Organic Wastes. (Gobar Gas Research Station, Ajitmal, Etawah (U.P.), India, 1971), p. 66. Mr. Singh made these estimates at 1971 prices.

[8] The principal is amortized over 5 years at 10% interest. No maintenance costs are included. In fact about the only maintenance needed, other than periodically removing the accumulated straw, is an occasional coat of paint.

[9] Assuming 330 days of operation per year (to allow for cleaning). The bio-gas was assumed to contain 60% methane having an energy value of roughly 600 BTU/ft^3.

[10] Figures at the rate of 2¢ per kilowatt-hour.

[11] The added value of the digested manure as fertilizer is not included. The nitrogen content of it varies so much that a meaningful estimate isn't possible. The cost per kwhr is figured on the gas production for 10 years. Productive lifetimes for a generating plant ought to be much longer. Nor have I taken into consideration that the bio-gas will be used at less than 100% efficiency. To convert it to electricity using a diesel generator like Fry did, these costs ought to be tripled since the engine is only about 30% efficient.

L. John Fry's) resulting in the production of large quantities of bio-gas which could then be used for generating electricity or heating. The problem of disposing of large quantities of digested slurry would remain, but perhaps as fertilizer becomes more expensive, farmers will become more interested in it for fertilizer. Also the slurry ought to be much easier to handle than manure.

Estimating the size of a bio-gas plant can be quite a chore. The best way, of course, would be to daily collect all the manure to be dumped into the digestor and measure its volume. After having done this for a few days, a reasonable estimate as to the size of the plant could be obtained. For those who would rather not go to this trouble, two tables are provided below for average output per animal per day. The number of livestock units gives an easy way to compare manure production for animals of different sizes. On the average, a dairy cow produces 12 times more manure than a calf or 120 times more than broiler chicken. Obviously these figures are not terribly accurate, but they can give a reasonable approximation to the amount of digestible material.

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[12] This is the size of Fry's installation. The estimate for its initial cost is my own. Most of the money goes for electric generating equipment, engines and pumps. The actual bio-gas plant costs less. See L. John Fry's <u>The Practical Building of Methane Power Plants for Rural Energy Independence</u>.

Table 3[13]

Average Adult Animal	Lbs/day/animal urine	feces	Total Solids per Day	Livestock Units
Bovine (1000 lbs)	20	50	10	
Bulls				130-150
Dairy Cows				120
Under 2 years				50
Calves				10
Swine (160 lbs)	4.0	7.5	1.5	
Boar, sow				25
Pig, larger than 160 lbs				20
Pig, smaller than 160 lbs				10
Weaners				2
Fowl				
Geese, turkey (15 lbs)	0.5		.18	2
Layer Chicken (3.5 lbs)	0.3		.1	1.5
Broiler chicken (1.5 lbs)	0.1		.04	1
Humans (150 lbs)				
	2.2	0.5	.3	5

[13] After L. John Fry and Richard Merrill in Methane Digesters for Fuel Gas and Fertilizer (Pescadero, California, 1973), p. 14.

Table 4[14]

Type of Manure	Ft^3 of Bio-gas per pound of dry matter (total solids)
Pig	6.0 - 8.0
Cow	3.1 - 4.7
Chicken	6.0 - 13.2
Conventional sewage	6.0 - 9.0

[14] After L. John Fry and Richard Merrill in Methane Digesters for Fuel Gas and Fertilizer. (Pescadero, California, 1973), p. 19. These numbers should not be taken too literally. The amount of bio-gas from a pound of dry manure also depends on what the animal has been fed. In general, grain-fed animals produce a manure that will make more bio-gas and a fertilizer with a higher nitrogen content.

It might also be possible to build methane generators in place of or in addition to the conventional municipal sewage treatment plant. Singh reports that municipal sewage is in general too dilute to be of use in a bio-gas plant,[15] but there is no reason that the difficulty could not be overcome by simply evaporating some of the water or by letting the solids settle out. Then a sewage plant could well become a productive asset rather than simply a taxpayer's headache. A report, which I was not able to verify, has the city of Los Angeles using exactly such a scheme--the bio-gas is used to power generators which in turn provide electricity for the sewage plant.

One problem with a bio-gas plant in Montana would be maintaining it at its optimum temperature for methane production. Theoretically, with enough insulation, not a whole lot of energy would be needed to heat it. Using Fry's idea of circulating his diesel engine's cooling water through the slurry may provide substantial heat. Exactly how much energy is needed is contingent on size, of course, and on its architecture. That remains a problem for the individual builder to solve.

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[15]"Plowboy Interview with Ram Bux Singh," The Mother Earth News, XVIII (November, 1972), p. 9.

epilogue

Hopefully the preceding pages have illuminated a few of the myriad ways that solar energy can be put to practical use. There is no pretense of being an exhaustive treatise on solar energy— that would need many volumes and someone more knowledgeable than I. But the paper does adumbrate some of the more interesting and economically promising utilizations of solar energy which can be used in Montana, the climate notwithstanding. Also I hope it has been unequivocally demonstrated that solar energy is both monetarily and ecologically workable and will become even more so in the future.

Let me argue once more for the practicability of solar energy, using the specific example of solar space heating. If a home owner were to install a flat plate collection system that would supply 50% of his heating needs, then no matter what natural gas, fuel oil or electricity prices do in the future (and they will inevitably rise), the sun will give energy at a constant cost, the cost itself depending on the longevity of the system. So 50% of the homeowner's heating bill cannot rise. That is surely a powerful argument for using solar space heating.

But it isn't sufficient to consider only the current economics of solar energy. The long term costs of conventional energies will

increase as the recent "energy crisis" vividly proved. Thus, while solar energy may now be somewhat expensive and marginally feasible, in the future it almost certainly will show itself as the most economic energy. That it is also the more ecologically compatible energy cannot be disputed.

What can be done to implement use of it? All applications of solar energy require initial capital investment beyond that of its equivalent in conventional energy production equipment, that is, it is capital intensive. There are no fuel costs of course. If at least the same tax breaks were given to the individual user of solar energy as are given to corporate capital investment, then that would be one added incentive for its use. Perhaps its use could even be more emphatically encouraged by making the tax breaks on the equipment for solar energy greater than conventional energy equipment. It deserves deliberation at any rate.

It may be argued that such a break is discriminatory. So be it. Surely Montanans must have some voice in what the future means of producing energy will be. The past has shown that major power companies respond only to public pressures when they respond at all. If such gentle prodding is applied, then it is at least remotely possible that the larger power companies as well as the individual user will react with sympathy. That is worth a modicum of effort at least.

Beyond this the ways of stimulating interest in alternative energies are somewhat limited. Research could undoubtedly be state-sponsored and pioneers in using alternative energy could be subsidized, but I suspect that appropriating the dollars for these purposes, especially the latter, would prove to be difficult. It remains a problem for the controllers of the state's purse to resolve.

If solar energy is to make any significant contribution to energy production in Montana before long, the message of this paper is clear: application must begin now.

appendix 1

The orientation of the sun with respect to any surface is given by:[1]

$$\cos\theta = \sin\delta \sin\phi \cos s - \sin\delta \cos\phi \sin s \cos\gamma + \cos\delta \cos\phi \cos s \cos\omega + \cos\delta \sin\phi \sin s \cos\gamma \cos\omega + \cos\delta \sin s \sin\gamma \sin\omega$$

where: $\theta \equiv$ angle between the incident beam and the normal to the surface; $\phi \equiv$ latitude (north positive); $\delta \equiv$ declination, the angle that the sun at solar noon makes with the equatorial plane (north positive); $s \equiv$ angle between the horizontal and the surface; $\gamma \equiv$ surface azimuthal angle (zero point due south, east positive, west negative); $\omega \equiv$ hour angle (solar noon zero, mornings positive, afternoons negative).[2]

The declination δ is given in degrees by:[3]

---

[1]This equation can be found in many of the references I've cited, though perhaps in a slightly different form. I got it from Solar Energy Thermal Processes by John Duffie and William Beckman. For geometry enthusiasts, it is a good project to derive it.

[2]Each hour the sun travels 15° so one hour is equivalent to $\omega = 15°$.

[3]P. I. Cooper, "The Absorption of Solar Radiation in Solar Stills," Solar Energy, XXII: 3 (1969).

$$\delta = 23.45 \sin \left\{ \frac{2\pi(284+n)}{365} \right\}$$

where n is the day of the year.

For a horizontal surface, the equation reduces to:

$$\cos \theta_z = \sin \delta \sin \phi + \cos \delta \cos \phi \cos \omega$$

where θ_z is the zenith angle (the angle between the incident beam and the vertical). Another angle sometimes useful is the altitude angle, α, defined as $90° - \theta_z$.

The length of a day can be found using the equation for θ_z. Since $\theta_z \leq |90°|$, we get for $\theta_z = 90°$ (its maximum value corresponding to the position of the sun at sunrise or sunset):

$$\cos \omega = - \frac{\sin \delta \sin \phi}{\cos \delta \cos \phi} = -\tan \delta \tan \phi$$

or

$$\omega = \cos^{-1} (-\tan \delta \tan \phi).$$

Then, since each hour is equivalent to 15°, the length of the day L is:

$$L = \frac{2}{15} \cos^{-1} (-\tan \delta \tan \phi)$$

appendix 2: direct beam radiation

As an exercise in futility I calculated the total yearly amount of direct beam radiation using two unsatisfactory methods. The first method went as follows: values for direct beam radiation on a surface perpendicular to the beam have been tabulated for a standard (i.e., clear), cloudless atmosphere and various optical air masses.[1] Knowing that the optical air mass is proportional to the CSC α, where α is the solar altitude angle (see appendix 1), and knowing the position of the sun for specified times during the day, it is possible to correlate the sun's position with a value for direct beam radiation. Now by calculating α with the equations in appendix 1 and comparing CSC α with the optical air masses in the table reproduced below, we can come up with a rate for direct beam radiation for each day of the year and, hence, for the entire year. Note that this value is the theoretical maximum. It does not consider the effects of cloud cover. The latitude used in this calculation was 45° and the time interval was the length of the

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[1]The optical air mass is the amount of air that sunlight must travel through. Using table 3.2 on p. 37 of Introduction to the Utilization of Solar Energy, optical air mass can be correlated with a value for direct beam radiation.

day divided by 200. The maximum amount of direct beam radiation is then 5.14×10^5 langleys per year. This figure is only to be used for establishing the <u>maximum</u> amount of direct beam radiation—it is worthless for anything else.

Table 1[2]

Solar altitude α, degrees	Optical air-mass path* m $\sim \csc \alpha$	*Standard, Cloudless Atmosphere*			*Industrial, Cloudless Atmosphere*			*Through Complete Overcasts, Blue Hill, Average Total Insolation on Horizon*			
		Direct, perpendicular radiation I, B/hr ft²	Diffuse on horizontal I_s, difference, B/hr ft²	Total on horizontal W_s, B/hr ft²	Direct, perpendicular radiation I, B/hr ft²	Diffuse on horizontal I_s, difference, B/hr ft²	Total on horizontal W_s, B/hr ft²	Cirro-stratus W_s, B/hr ft²	Alto-cumulus W_s, B/hr ft²	Strato-cumulus W_s, B/hr ft²	Fog W_s, B/hr ft²
5	10.39	67	7	13	34	9	12	—	—	—	—
10	5.60	123	14	35	58	18	28	—	—	15	10
15	3.82	166	19	62	80	24	45	50	35	25	15
20	2.90	197	23	90	103	31	64	70	50	35	20
25	2.36	218	26	118	121	38	89	95	65	40	20
30	2.00	235	28	146	136	44	112	120	75	50	25
35	1.74	248	30	172	148	48	133	145	90	60	30
40	1.55	258	31	197	158	52	154	165	105	70	35
45	1.41	266	32	220	165	55	172	185	115	80	40
50	1.30	273	33	242	172	58	190	205	130	85	40
60	1.15	283	34	279	181	63	220	235	150	100	45
70	1.06	289	35	307	188	69	246	260	160	110	50
80	1.02	292	(35)	(322)	195	—	—	—	—	—	—
90	1.00	294	(36)	(328)	200†	—	—	—	—	—	—

* Smithsonian Meteorological Tables, 6th rev. ed., 1951, p. 422.
† 192 would be more consistent with the curve from 70° down.

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[2] A. M. Zarem and Duane D. Erway, <u>Introduction to the Utilization of Solar Energy</u>. (New York, McGraw-Hill), p. 37.

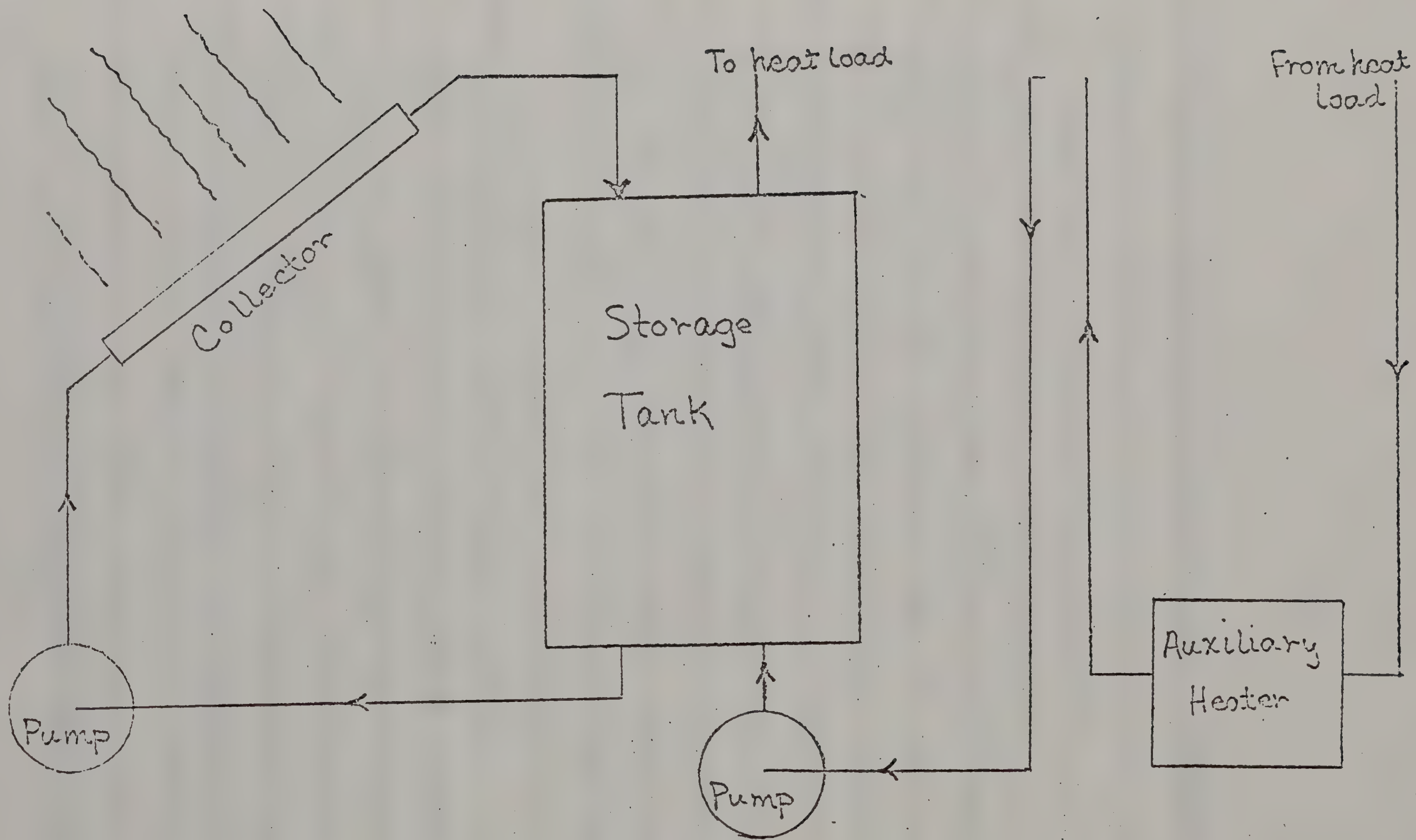
The second method went as follows: Tybout and Löf in their simulation of a solar heated house found that the diffuse component of sunlight could be satisfactorily represented by $C_{diffuse} = 0.78 + 1.07\ \alpha + 6.17\ CC$ where α is the solar altitude angle in degrees and CC is cloud cover, 0 being a clear sky and 10 a completely overcast sky.[3] Then by subtracting the diffuse component from the total radiation, we are left with the direct beam component of solar radiation. Now by using total hemispheric insolation data for Great Falls and figuring the orientation of the sun for each hour that the data is taken, we can calculate the rate of direct beam radiation on a surface oriented so that it is always perpendicular to the beam. I got langleys per year as a 12 year average for Great Falls. This is just the sort of information that we need to figure the practicalness of any system using focusing collectors. If the overall efficiency of a system employing focusing collectors is 25%, then to produce kwhr of energy in one year, we need m^2 of collector. This figure, too, stands on shaky legs. The only way to arrive at a reliable estimate is to actually measure direct beam insolation with a pyrheliometer.

[3] G. O. G. Löf and R. A. Tybout. "A Model for Optimizing Solar Heating Design," ASME Paper No. 72-WA/Sol-8. (New York, ASME), p.2.

appendix 3: computer simulated performance of a sun heated house

Back in the chapter on solar heating and cooling I gave a cost of \$2.00 for 10^6 BTU using a combination of solar and natural gas heat. The figure was gotten by using the transient simulation program (TRNSYS) developed by the Solar Energy Lab at the University of Wisconsin. The system that I modeled is schematicized in figure 1, and I used the weather data that is available for Great Falls to evaluate its performance. Note that this solar heating system is very simple, probably not so complex as one that would actually be used in Montana, but nevertheless, it provides a good approximation of any similar solar heating system.

Earlier we saw basically how a flat plate collection system operates; however, in order to numerically evaluate the system, it must be mathematically described. Of course, it would be better to actually construct the system, and by measuring climatic variables, heating load and the parameters of the system, to determine its effectiveness. But, since no solar heating system is used anywhere in Montana, we'll have to do the best we can with a computer simulation and take the results we get with a grain of salt allowing for the approximateness of the results.



To heat load
From heat load
Collector
Storage Tank
Auxiliary Heater
Pump
Pump
Pump

Figure 1

Now let's specify the parameters of the heating system. Afterward I'll briefly explain how to find each of them and what their utility is:

<u>collector</u>

area	A_c
tilt of the collector, measured from the horizontal	α
collector loss coefficient	U_L
cover transmission factor times absorption factor	$\tau\alpha$
collector efficiency factor	F'
flow rate of water through the collector	$\dot{M}_c$

<u>storage tank</u>

storage tank volume	V
height to diameter ratio	R
tank loss coefficient	U
ambient temperature around the tank	T_{env}
storage fluid density	ρ

<u>heating load</u>

overall heat transfer coefficient	UA
room temperature	T_R

<u>heating load</u> (continued)

flow rate through load	$\dot{M}$
minimum storage temperature	T_{MIN}

In addition to these system parameters there are two climatic variables that we need for the numerical evaluation. They are hourly insolation data and temperature.

First let's consider the collector parameters: The area, in m^2, is the total area of the collector used to gather radiation. This parameter will be varied to find the optimum size of the system for least cost heat. The tilt factor measures the inclination of the collector to the horizontal. This angle has already been optimized by several people[1]--the collector should be tilted 10° to 15° plus the latitude of the place from the horizontal. For Great Falls, latitude about 47.5°, we'll assign a value of 60°. Note that near the optimum angle of orientation, the variation of the collector tilt has little effect on the heat collection capabilities of the system.

Now we come to the more difficult part of determining the collector parameters. U_L is found by considering the geometry of the collector, the materials from which the flat plate is made, and the

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[1]See for example R. A. Tybout and G. O. G. Löf, "Solar House Heating," <u>Natural Resources Journal</u>; W. A. Beckman and J. A. Duffi <u>Solar Energy Thermal Processes</u>; L. W. Butz, W. A. Beckman and J. A. Duffie, "Simulation of Solar Heating and Cooling Systems."

effectiveness of the collector's insulation. Neglecting edge effects, the overall collector loss coefficient is a function of: (1) the number of glass cover plates, (2) the flat plate to cover distance, (3) plate emissivity, (4) wind speed, (5) thickness of insulation and its conductivity, (6) the angle that the collector makes with the horizontal, (7) average plate temperature, and (8) ambient temperature. An empirical equation has been found by S. A. Klein[2] to predict heat losses through the collector top, U_t, in a temperature range of operation from 40°C to 130°C $\pm$ 0.2 watts $m^{-2}\,°C^{-1}$:

$$U_t = \frac{1}{\dfrac{N}{\dfrac{344}{T_p}\left[\dfrac{T_p - T_a}{N+f}\right]^{.31}} + \dfrac{1}{h_\omega}} + \frac{\sigma(T_p+T_a)(T_p^{\,2}+T_a^{\,2})}{\dfrac{1}{\varepsilon_p+0.0425N(1-\varepsilon_p)} + \dfrac{2N+f-1}{\varepsilon_g} - N}$$

where N is the number of glass cover plates on the collector,

T_p is the plate temperature in °K,

$f = (1.0-0.04\, h_\omega + 5.0\text{x}10^{-4} h_\omega^{\,2})(1.0 + 0.058\, N)$,

$h_\omega = 5.7 + 3.8$ (wind velocity in m sec^{-1}),

ε_g is the emittance of glass,

ε_p is the emittance of the plate,

---

[2]See S. A. Klein, J. A. Duffie and W. A. Beckman, "Transient Considerations of Flat-Plate Solar Collectors." Also look at Hottel and Woertz's paper, "The Performance of Flat-Plate Solar Collectors," and Duffie and Beckman's Solar Energy Thermal Processes.

T_a is the ambient temperature in °K, and

σ is the Stefan-Boltzmann constant.

Now we see that the number of glass cover plates does affect the efficiency of the collector in that more plates retard heat losses. Later, we'll see that they also affect the amount of sunlight reaching the flat plate--the more cover plates, the less light reaching the collector. For our collector we'll let N=3. That's not a capriciously gotten number, but Tybout and Löf's work seems to indicate that for severe climates, 3 or possibly 4 cover plates are needed.[3] For this simulation, the emissivity of glass will be 0.88 and the emissivity of the plate is 0.10 over the range of temperatures at which the collector operates. The average wind velocity during January, the month we'll use for the simulation, is 15 mph or 6.7 m sec^{-1}. T_a is simply the temperature in °K. Given all these parameters we are still hard put to come up with a number for U_t because T_p is as yet unspecified, in fact it varies continuously with the climatic variables, flow rate, and the temperature of the incoming heat transfer fluid. Thus, an iterative process is necessary to find it as we'll later see. Rather than do this, U_t will be taken to be a

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[3]See Tybout and Löf, "Solar House Heating."

constant, the value of which has been previously established by Duffie and Beckman in Solar Energy Thermal Processes for various climatic conditions and plate temperatures.[4] But to be certain that we don't underestimate U_t, therefore overestimating the collector's performance, a relatively high value will be picked, U_t = 1.9 watts $m^{-2} {}^\circ C^{-1}$, corresponding to a wind speed of 10 m sec^{-1} and an ambient temperature of −20°C and a plate temperature of 100°C. In fact when water is used as a heat transfer fluid, the plate temperature cannot exceed 100°C by much unless the system is pressurized. Furthermore, for likely values of T_p, wind speed, T_a, etc., U_t is not a quickly varying function, but it remains relatively stable for a given collector.[5]

The bottom loss coefficient, U_B, is given by $U_B = A_c k/\ell$ where k is the conductance of the insulating material and ℓ is its thickness. A reasonable value for k is 0.045 watts $m^{-1} {}^\circ C^{-1}$, so if ℓ = 5 cm, U_B = .9 watts $m^{-2} {}^\circ C^{-1}$.

The overall loss coefficient is now $U_L = U_t + U_B$ or U_L = .9 watts $m^{-2} {}^\circ C^{-1}$ + 1.9 watts $m^{-2} {}^\circ C^{-1}$ = 10.08 $kJm^{-2} {}^\circ C^{-1}$ hr^{-1}. For more detail see the reference cited in the footnotes, especially Solar Energy Thermal Processes.

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[4] See Duffie and Beckman. Solar Energy Thermal Processes, p. 7.25.

[5] The average wind velocity in January at Great Falls is 6.7 m sec^{-1}, and the mean temperature is −6.6°C. Given these conditions U_t varies from 1.3 watts $m^{-2} {}^\circ C^{-1}$ for T_p = 10°C to 2.00 watts $m^{-2} {}^\circ C^{-1}$ for T_p = 120°C.

Now for $\tau\alpha$. For N cover plates the effective transmission factor is

$$\tau_N = \frac{(1-i)}{1+(2N-1)i}$$

where i is the index of refraction of the material used for cover plates. This equation can be derived from Fresnel's equations; Hottel and Woertz do this and also consider the absorption of light by the cover plates.[6] τ_A, the fraction of incident solar radiation allowed through the cover plates, is given by $\tau_A = e^{-KL}$ where K is the extinction coefficient of the covers and L, their total thickness. To a good approximation[7] the total transmittance, $\tau' = \tau_A \cdot \tau_N$. Finally, with a plate of absorptance α' and considering multiple reflections of the incident diffuse radiation,[8] we get the transmittance absorptance product $\tau\alpha$:

$$\tau\alpha = \tau'\alpha' \sum_{n=0}^{\infty} \left[(1-\alpha')\rho_d \right]^n = \frac{\tau'\alpha'}{1-(1-\alpha)\rho_d}$$

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[6] H. C. Hottel and B. B. Woertz. "The Performance of Flat-Plate Solar-Heat Collectors," Transactions of the ASME, LXIV (February, 1942), pp. 96-97.

[7] Ibid., p. 96.

[8] Duffie and Beckman, Solar Energy Thermal Processes, p. 69.

where ρ_d is the reflection of diffuse radiation. Now we must make some approximations again for ease of calculation. Both τ' and α' remain nearly constant for angles of incidence up to 60°. For larger angles they begin to increase. Since the major portion of radiation will strike the collector at angles less than 60°, we can take τ' and α' to be their values at 60° to a good approximation.[9] Again we err on the side of overestimation rather than underestimation of this loss because the values of τ' and α' at 60° are somewhat less than their maximum. For 3 cover plates each of .23 cm thickness and extinction coefficient .161 cm^{-1}, let $\tau' = .70$, and we'll let $\alpha' = .9$. Similarly ρ_d behaves much as τ' and α' so we'll also use its value at 60° which is 0.29 for 3 cover plates.[10] Then $\tau\alpha = .65$.

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[9] Only early in the morning and late in the afternoon is the angle of incidence greater than 60°. The fraction of the day's total radiation at these times is quite small. For example, at 8 o'clock (solar time) on January 1, the angle of incidence is 57°. For 1956 the amount of radiation that had been measured up to this time was less than 4 langleys. Similarly after 4 o'clock solar time, the amount of radiation was less than 3 langleys. The total amount for that day was 137.3 langleys so that any significant error introduced by this assumption is limited to less than 5% of the total radiation. Furthermore, the amount of radiation at this hour may not be sufficient to begin operating the collector.

[10] These values for α', τ' and ρ_d can be computed, or they can be found in chapters 5 and 6 of Solar Energy Thermal Processes where they have already been calculated.

Notice that the plate absorptivity and emissivity were assumed to be 0.90 and 0.10, respectively. This you may recognize as characteristic of a selective surface. Looking back at the table of selective surfaces, we see that there are several that meet or exceed these requirements. Thus, since a selectivly-surfaced collector's performance will be tremendously better than one that isn't, it is reasonable to give our collector this advantage, particularly in Montana's climate.

Before F' is specified, we must know something about the geometry of the collector. It is sketched in figure 2. For this design the efficiency factor is:

$$F' = \frac{1/U_L}{\omega\left[\frac{1}{U_L(D+\{\omega-D\}F)} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}}\right]}$$

where ω is the spacing of the tubes, D is the tube's outside diameter, C_b is the conductance of the bond between the tube and plate, D_i is the tube's inside diameter, and h_{fi} is the heat transfer coefficient between the tube and the water. F is the standard fin efficiency for straight fins with rectangular profile given by

$$F = \frac{\tanh\left[m(\omega-D)/2\right]}{m(\omega-D)/2}$$

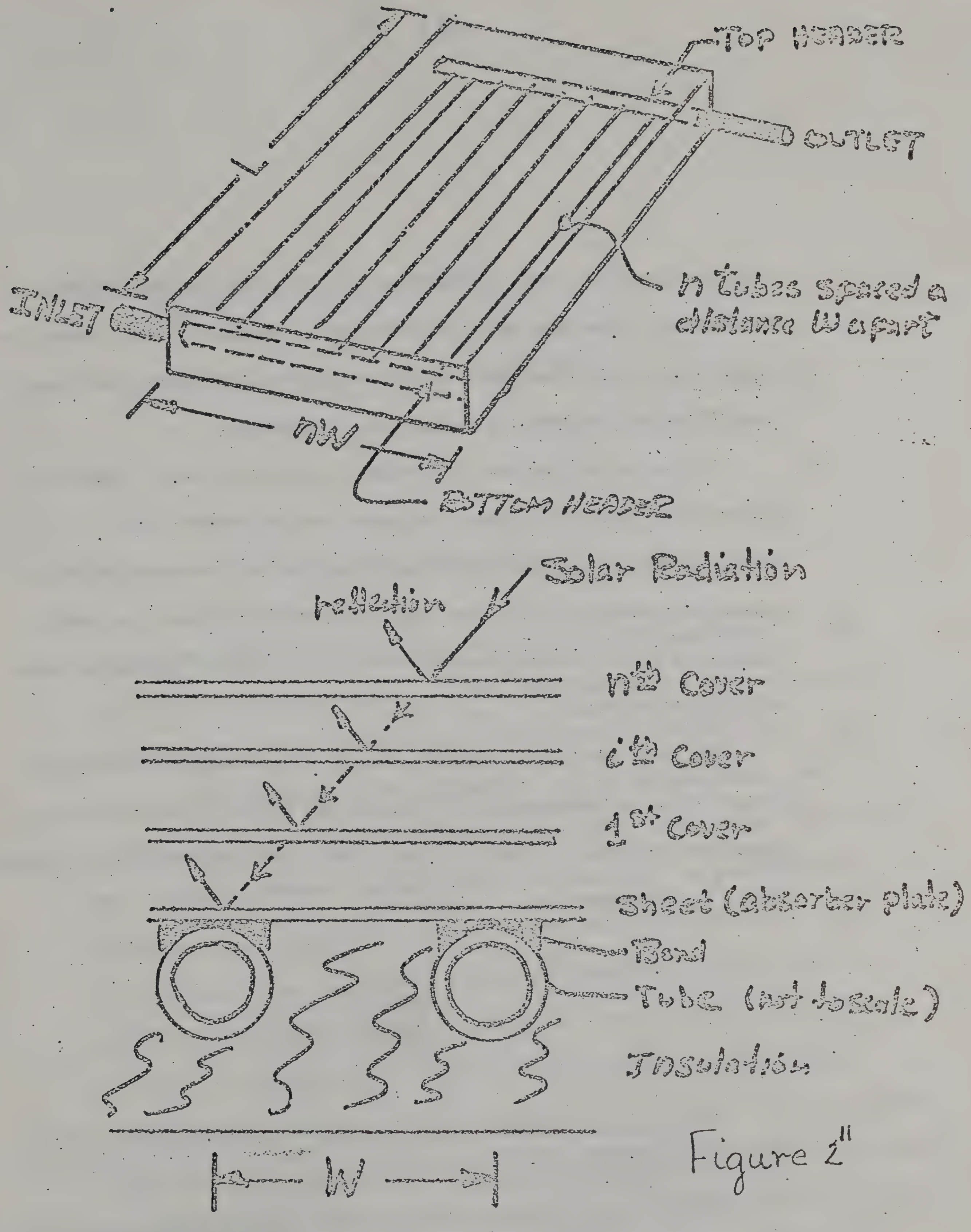

Figure 2[11]

[11] The figure is from W. A. Beckman and J. A. Duffie, Solar Energy Thermal Processes (Solar Energy Laboratory, University of Wisconsin, Madison, 1974). p 7.7.

ω and D being the same as above and $m^2 = U_L/k\delta$, where δ is the thickness of the fin and k is Boltmann's constant.[12] It should be noted that for a specific fluid flow rate and collector design, the efficiency factor is essentially a constant.

It is not my purpose to design a collector here. Suffice it to say that a well-designed collector has efficiencies F' of .8 or more, in fact .95, the efficiency I assume in this simulation, is easily attainable. For those who are curious or want to verify this, see Solar Energy Thermal Processes or Bliss' paper on plate efficiency factors.

For calculation of both F' and U_L a knowledge of the plate temperature is necessary, the derivation of which requires some numerical analysis. Klein[13] has shown that the mean plate temperature, T_m, is given by

$$T_m = T_{in} + \frac{Q_U A_C}{U_L F_R} \left(1 - \frac{F_R}{F'}\right)$$

[12] For a more comprehensive treatment again see <u>Solar Energy Thermal Processes</u>, chapter 7, a book on heat transfer, or Bliss' paper on flat plate collector efficiencies.

[13] S. A. Klein. "The Effects of Thermal Capacitance Upon the Performance of Flat-Plate Solar Collectors." M.S. Thesis, University of Wisconsin, 1973.

where

$$F_R = \frac{GC_P}{U_L}\left(1 - \exp(-U_L F'/GC_P)\right)$$

and

$$Q_U = A_C F_R \left[S - U_L (T_{in} - T_a) \right].$$

T_{in} is the temperature of the fluid entering the collector. The new factors introduced are: G, the flow rate per unit area of the collector; C_P, the specific heat of the heat transfer fluid; and S, the rate of incident solar radiation. F_R is the collector heat removal factor and Q_U is the useful heat gain. With this information an iterative process can be used to evaluate U_L. A good initial guess for T_m is $T_{in} + 5°C$, T_{in} of course being the temperature of the storage tank. T_m varies slightly throughout the day, but its influence on U_L is negligible. Thus, the assumptions for constant U_L and F' are justified. Both U_L and F' could be found from T_m which is gotten by the iterative process outlined above—it requires a masochist for the job, however. Since both of them have been found by others for various collector geometries, climatic variables, etc., it is much simpler to use their results saving computer time and work in the process.

That finally disposes of the collector parameters.

Except for one last thing. Someone may ask: what about all this glass? Does it ever get dirty and what effect does that have on collector performance? Yes, the glass gets dirty but the effect on collector performance is almost negligible amounting to no more than 5% and usually less than 1%.[14] To account for these effects, let's assume that dust and dirt will reduce the sunlight reaching the collector plate by 2%. Then we must simply subtract this 2% from the amount of solar radiation hitting the collector, or equivalently reduce the transmittance-absorptance product to 0.63.

Now we've come to the storage tank. Extrapolating from the work of Tybout and Löf, who found the optimum size of storage to be from 10 lbs. of water to 15 lbs. for every ft^2 of collector area, we'll set the storage volume at 58.7 kg of water for every m^2 of collector area. Since the size of storage has a relatively unimportant effect on the cost of solar heat when it's <u>near</u> the optimum size,[15] the size of storage will be constant for a given

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[14] See Hottel and Woertz. "The Performance of Flat-Plate Solar-Heat Collectors," <u>Transactions of the ASME</u>, LXIV: 91 (February, 1942), p. 100, and Duffie and Beckman, <u>Solar Energy Thermal Processes</u>, p. 7.57.

[15] See Tybout and Löf, "Solar House Heating," pp. 293-97, for the effect of storage size on the cost of solar heat.

collector area. At least as important is the elimination of one more cost parameter, and hence, savings in computer time. The height-to-diameter ratio of the tank is also important because the TRNSYS program treats it as if it is stratified. The degree of stratification depends on this ratio;[16] also, heat losses from the tank (assumed to be cylindrical) depend on the surface area and the amount and conductance of the insulation surrounding it. For the storage tank the loss coefficient will be 1.44 kJ/hr m^2°C, and its minimum temperature will be 21.7°C.

Lastly, the house will be kept at a temperature of 21°C and will have an overall heat transfer coefficient of 1200 kJ/hr°C (about 15,100 BTU/DD). This is a medium size house. How a flat plate collection system would perform on another house or building of a different size or a building that is kept at a different temperature wasn't studied.

It is important to make provisions to drain the collector when it isn't operating if the system I've illustrated in figure 1 is used; otherwise, the water in the collector may freeze and, consequently, burst the tubes. That would ruin a large and expensive part of the heating system just as effectively as water freezing in an engine block ruins it. It would be better to use a

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[16] See section 9.3 in Solar Energy Thermal Processes.

heat exchanger and an antifreeze solution in the collectors, but as this complicates the analysis and increases the cost of the heat, I haven't simulated performance of such a system. Should a heat exchanger be included, it would lower the overall efficiency of the system, but on the positive side, it would surely be much safer.

To reduce computing time I've run this system for two months: January 1954, which represents Great Fall's winters at their worst as far as heating loads go, and January 1956, which was about an average winter temperature-wise.[17] In tables 3 and 4 the daily performance of a system using 60 m^2 of collector is tabulated fo two weeks in January 1954, and the corresponding two weeks in January 1956. Then in table 5 is the monthly performance of the same system from September 1955 to June 1956. Later we'll refer back to this system. To really obtain a plausible approximation of a solar heating system, it is necessary to evaluate it over the entire year or at least during the entire heating season. Because of the computer expense involved, however, I've only done it once.

In tables 3 and 4 the actual amount of energy put into heating the house is the sum of the useful solar heat (column 2) and the

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[17]In January 1954 the average temperature was 9.7°F and in January 1956, 21.2°F. The average January temperature for the period 1941-1970 is 20.5°F. January 1954 is not quite all of January--radiation data for the first three days were missing, so I added the first three days of February to compensate.

auxiliary heat (column 5). This should equal the sum of the storage losses, the change in the storage tank energy, and the heating load with allowances made for round-off errors. The fractional amount of the sun's energy collected by the system is simply the useful solar heat divided by the radiation on a surface tilted 60° due south. Table 6 shows the simulated performances of solar heating systems of various sizes. A little later we'll use these figures to determine the energy costs for the systems.

At last we've arrived at the key argument for the use of solar house heating in Montana. What will it cost? The initial investment in a solar heating system will be much greater than an equivalent conventional furnace (exactly how much greater we'll shortly see), but the advantage of having a free and perpetual source of fuel may offset the disadvantage of the larger initial cost. An important point to consider is the lifetime of the system. Conventional furnaces eventually wear out and so do solar systems. As yet there is not enough experience with solar energy to predict how long they will actually last, but it seems safe enough to assume a 20 year lifetime, disallowing accidents such as broken cover plates. Löf's and Thomasen's solar heating systems have been in operation for 15 years and at last report show no signs of quitting. Australian water heating systems have operated for in excess of 15 years with essentially no maintenance and also don't

Table 2

Performance of Various Sizes of Solar Heating Systems During January 1956

Collector Area (m^2)	Storage Size (m^3)	Useful Solar Heat ($kJx10^6$)	% Solar Heat	% of Sun's Energy Collected	Auxiliary Heat Required ($kJx10^6$)	Cost of Auxiliary (using MPC's natural gas rates)
30	1.76	7.83	34.3	47.5	15.14	$22.39
40	2.35	10.13	44.0	46.1	12.90	18.80
50	2.94	12.54	54.7	45.7	10.44	15.60
60	3.52	14.74	64.0	44.7	8.29	12.82
70	4.11	16.81	72.7	43.7	6.30	10.24
80	4.70	18.63	80.0	43.4	4.60	8.06
90	5.28	20.09	85.5	40.6	3.33	6.40
100	5.87	21.32	90.0	38.8	2.32	5.10
110	6.46	22.37	93.4	37.0	1.51	4.05
120	7.05	23.30	96.3	35.3	0.86	3.20
140	8.22	24.86	99.4	32.2	0.14	2.97

The heat required to keep the house at 21°C in January was 23.04 x 10^6 kJ. At MPC's rates this amounts to $31.92 for gas heat or $104.17 for electric heat.

Tot[illegible] solar radiation on a horizontal surface was 20 [illegible] x 10^4 [illegible].

T[illegible]l solar radiation on a horizontal surface was 2[illegible]6 x 10^4 kJ m^{-2}.

Table 3

Simulated Daily Performance of a Solar Heating System during Two Weeks in January 1956

(collector area 60 m^2)

Day	Useful Solar Heat ($kJx10^5$)	Change in Storage Tank Energy ($kJx10^3$)	Storage Losses ($kJx10^3$)	Auxiliary Heat ($kJx10^5$)	Total Heat Required ($kJx10^5$)	% Solar Heat	% Sun's Energy Collected by the Heating System
13	5.63	-59.39	10.68	0.01	6.13	99.8	46.9
14	2.28	-40.92	4.59	2.14	7.12	69.9	39.6
15	4.39	1.13	2.92	6.66	10.91	40.0	41.6
16	1.21	- 1.72	1.11	10.33	12.09	14.6	24.6
17	4.16	1.39	2.79	7.21	10.82	33.4	40.3
18	4.07	3.94	3.53	3.25	6.89	52.8	45.5
19	6.03	-34.81	7.20	2.12	6.01	64.7	47.6
20	6.71	89.4	9.92	0.52	6.74	92.3	47.6
21	4.34	-55.2	6.12	1.06	7.85	86.5	42.8
22	3.21	- 2.64	2.53	4.35	7.79	44.2	41.5
23	6.03	47.74	9.59	2.29	5.58	59.0	50.8
24	3.66	-43.60	6.85	2.37	6.10	61.1	42.1
25	6.12	-55.96	6.46	0.22	6.98	96.8	47.0
26	7.03	33.38	8.44	1.54	8.15	81.1	46.7
27	4.77	18.30	4.59	3.09	9.55	67.6	44.2

Table 4

Simulated Daily Performance of a Solar Heating System during Two Weeks in January 1954

(collector area 60 m^2)

Day	Useful Solar Heat ($kJx10^5$)	Change in Storage Tank Energy ($kJx10^3$)	Storage Losses ($kJx10^3$)	Auxiliary Heat ($kJx10^5$)	Total Heat Required ($kJx10^5$)	% Solar Heat	% Sun's Energy Collected by the Heating System
13	2.50	-30.76	4.39	2.88	8.41	65.8	38.1
14	1.44	- 7.0	1.18	10.26	11.76	12.8	28.3
15	1.32	- 0.04	1.11	13.01	14.37	9.5	23.5
16	2.10	0.05	1.53	11.89	13.92	14.6	29.7
17	2.20	- 0.09	1.65	10.98	13.18	16.7	31.0
18	5.51	1.50	3.60	8.14	13.46	39.5	41.1
19	4.10	- 0.41	2.72	9.18	13.29	30.9	38.7
20	7.24	3.85	4.99	8.64	15.44	44.0	43.8
21	4.33	- 3.64	2.93	9.67	14.33	32.5	40.6
22	3.10	- 0.68	2.11	10.34	13.49	23.4	37.0
23	3.32	0.37	2.10	10.78	14.03	23.2	37.5
24	7.77	4.00	5.51	7.55	14.85	49.2	43.0
25	6.97	- 1.68	5.07	7.35	14.42	49.0	42.1
26	6.25	0.65	6.48	4.14	9.15	54.8	52.0
27	2.49	0.03	2.51	8.18	12.10	32.4	32.1

Table 5

Simulation of a Solar Heating System from September 1955 to June 1956 (Collector Area $60m^2$)

Month	Useful Solar Heat ($kJx10^6$)	% Solar Heat	% Sun's Energy Collected	Auxiliary Heat Required ($kJx10^6$)	Heating Load ($kJx10^6$)
September	8.97	100.0	8.2	0.0	7.07
October	9.27	100.0	23.9	0.0	10.46
November	4.60	20.2	32.1	19.92	24.96
December	2.58	10.7	26.3	21.30	23.85
January	3.12	13.1	28.7	20.59	23.68
February	6.90	36.3	44.9	10.84	17.00
March	10.17	70.5	38.9	8.30	17.98
April	12.24	87.6	33.3	1.67	13.51
May	13.61	82.7	22.9	1.52	8.77
Total	71.46	42.9	28.8	84.14	147.28

appear ready to die. Anyway, I'll figure the costs over 20 years at 10% interest, for 10 years at 10%, and also the costs for cash purchase of the equipment.[18]

Tybout and Löf estimate that installed storage costs are about \$8 per m^2 of collector and that the extra controls, motors, pipes, etc. for the solar system cost \$250, independent of the size of the system.[19] Since the auxiliary furnace for the solar heating system and the furnace for the conventional system are common to both systems, we will ignore the costs of both for a comparison of solar heating costs relative to conventional heating. The most difficult part of the system for which to estimate a cost is the collector itself. The cost of flat plate collectors as they are now produced doesn't really give an accurate view of what they could be if they were mass-produced. On the other hand, coming up with an estimate for mass-produced collectors is difficult. So I'll use costs of \$20, \$30, \$40, and \$60 per m^2 in hopes that the actual costs for mass-produced collectors lie somewhere in that

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[18] The system costs are figured using $C = \frac{NPi}{1-(1-i)^{-N}}$ where C is the cost, N is the number of repayment periods (assumed to be 1 per year for ease), i is the interest rate, and P is the principal or initial cost.

[19] Tybout and Löf. "Solar House Heating," Natural Resources Journal. Also look at Solar Energy Thermal Processes, chapter 12.

range. Actually \$40 per m^2 is about what collectors, as they are now produced, cost and \$20 per m^2 is an estimate of what they could cost if produced on a larger scale.[20] Thus, our estimates should span the gamut of costs. Tables 6, 7, 8, and 9 tabulate the solar heating system cost for the various collector prices and amortization periods.

These systems look relatively expensive and considering the cost of natural gas in Montana, they do produce more expensive heat. For example, natural gas heating in January would cost \$31.92 at the present gas prices. For the same month, heat from a solar heating system would cost \$40.73.[21] Electric heating would cost \$104.17 so solar heating is considerably cheaper than it.

Let's also look at the simulation of our heating system for September 1955 to June 1956. Natural gas costs \$209.35 for the period. The auxiliary heating for the solar heating system costs \$123.47, and to this the yearly cost of the system must be added. For collector costs of \$20 per m^2, this amounts to a total of

[20] See Löf and Tybout, "Solar House Heating"; Duffie and Beckman, Solar Energy Thermal Processes, chapter 12; and Butz et al, "Simulation of Solar Heating and Cooling System," for further detail on collector costs.

[21] A collector area of 60 m^2 and a cost of \$20 per m^2 amortized over 10 years. For collector costs of \$30, 40, and 60 per m^2 and the same amortization period, the costs are \$49.41, 58.09, and 75.44, respectively. All conventional heat costs are at current Montana Power Company rates.

Table 6

Solar Heating System Costs for Collectors Costing \$20 per m^2 (\$1.86 per ft^2)

Area (m^2)	Initial Cost	Total Cost at 10% Amortized Over 20 Years	Total Cost at 10% Amortized Over 10 Years
30	\$1,090.00	\$ 2,560.63	\$1,773.98
40	1,370.00	3,218.39	2,229.61
50	1,650.00	3,876.17	2,685.30
60	1,930.00	4,533.94	3,140.99
70	2,210.00	5,191.72	3,596.67
80	2,490.00	5,849.49	4,052.36
90	2,770.00	6,507.26	4,508.05
100	3,050.00	7,165.04	4,963.73
110	3,330.00	7,822.84	5,419.58
120	3,610.00	8,484.58	5,875.11
140	4,170.00	9,796.13	6,786.48
160	4,730.00	11,111.68	7,698.08
180	5,290.00	12,427.27	8,609.48
200	5,850.00	13,742.82	9,520.88

Table 7

Solar Heating System Costs for Collectors Costing \$30 per m^2 (\$2.79 per ft^2)

Area (m^2)	Initial Cost	Total Cost at 10% Amortized Over 20 Years	Total Cost at 10% Amortized Over 10 Years
30	\$1,390.00	\$ 3,265.39	\$ 2,262.22
40	1,770.00	4,158.08	2,880.68
50	2,150.00	5,050.78	3,499.12
60	2,530.00	5,943.48	4,117.58
70	2,910.00	6,836.17	4,736.02
80	3,290.00	7,728.87	5,354.48
90	3,670.00	8,621.56	5,972.92
100	4,050.00	9,514.26	6,591.38
110	4,430.00	10,406.96	7,209.82
120	4,810.00	11,299.65	7,828.28
140	5,570.00	13,085.04	9,065.18
160	6,330.00	14,870.44	10,302.08
180	7,090.00	16,655.83	11,538.98
200	7,850.00	18,441.22	12,775.88

Table 8

Solar Heating System Costs for Collectors
Costing \$40 per m^2 (\$3.72 per ft^2)

Area (m^2)	Initial Cost	Total Cost at 10% Amortized Over 20 Years	Total Cost at 10% Amortized Over 10 Years
30	\$1,690.00	\$ 3,970.15	\$ 2,750.48
40	2,170.00	5,097.76	3,531.68
50	2,650.00	6,225.38	4,312.88
60	3,130.00	7,353.00	5,094.08
70	3,610.00	8,480.61	5,875.28
80	4,090.00	9,608.23	6,656.48
90	4,570.00	10,735.84	7,437.68
100	5,050.00	11,863.46	8,218.88
110	5,530.00	12,991.08	9,000.08
120	6,010.00	14,118.69	9,781.28
140	6,970.00	16,373.92	11,343.68
160	7,930.00	18,629.16	12,906.08
180	8,890.00	20,884.39	14,468.48
200	9,850.00	23,139.62	16,030.88

Table 9

Solar Heating System Costs for Collectors
Costing \$60 per m^2 (\$5.57 per ft^2)

Area (m^2)	Initial Cost	Total Cost at 10% Amortized Over 20 Years	Total Cost at 10% Amortized Over 10 Years
30	\$ 2,290.00	\$ 5,379.65	\$ 3,726.87
40	2,970.00	6,977.10	4,833.54
50	3,650.00	8,574.55	5,940.21
60	4,330.00	10,172.00	7,046.88
70	5,010.00	11,769.45	8,153.54
80	5,690.00	13,366.91	9,260.21
90	6,370.00	14,964.36	10,366.88
100	7,050.00	16,561.81	11,473.55
110	7,730.00	18,159.26	12,580.22
120	8,410.00	19,756.71	13,686.89
140	9,770.00	22,951.61	15,900.22
160	11,130.00	26,146.51	18,113.56
180	12,490.00	29,341.41	20,326.90
200	13,850.00	32,536.32	22,540.24

\$219.97, 280.52, or 350.17, depending on how the collector is paid for.[22]

This doesn't really tell the whole story, however. What we would like to know are the costs per unit of heat that a solar heating system produces. So we will figure just that for various cases. The efficiency of the gas furnaces in both the solar heating system and conventional system will be assumed to be 75%. That's a bit high but not unreasonable. To calculate the cost of solar heat only, we will assume a 20 year lifetime (that's probably too short as I've mentioned before), and to find the costs in January, the yearly cost of the system will be divided by the fraction of an average year's heating load contained in the month. The results of this for various solar heating systems are seen in figures 1, 2, and 3. Except for the case where the collectors are bought outright, and no bank collects interest on the money needed to buy them, the costs of solar heat don't look very favorable compared to gas heat, but when compared with electric heat, we see that they are favorable indeed.

We can be assured that conventional heat costs will not remain unchanged (consider the recent rate increase), so let's look to

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[22]For collector costs of \$30 per m^2, the costs are \$249.97, 329.35, 420.64; for \$40 per m^2, they are \$279.97, 378.17, and 491.12; and for \$60 per m^2, \$339.97, 475.81, and 632.07.

Figure 4

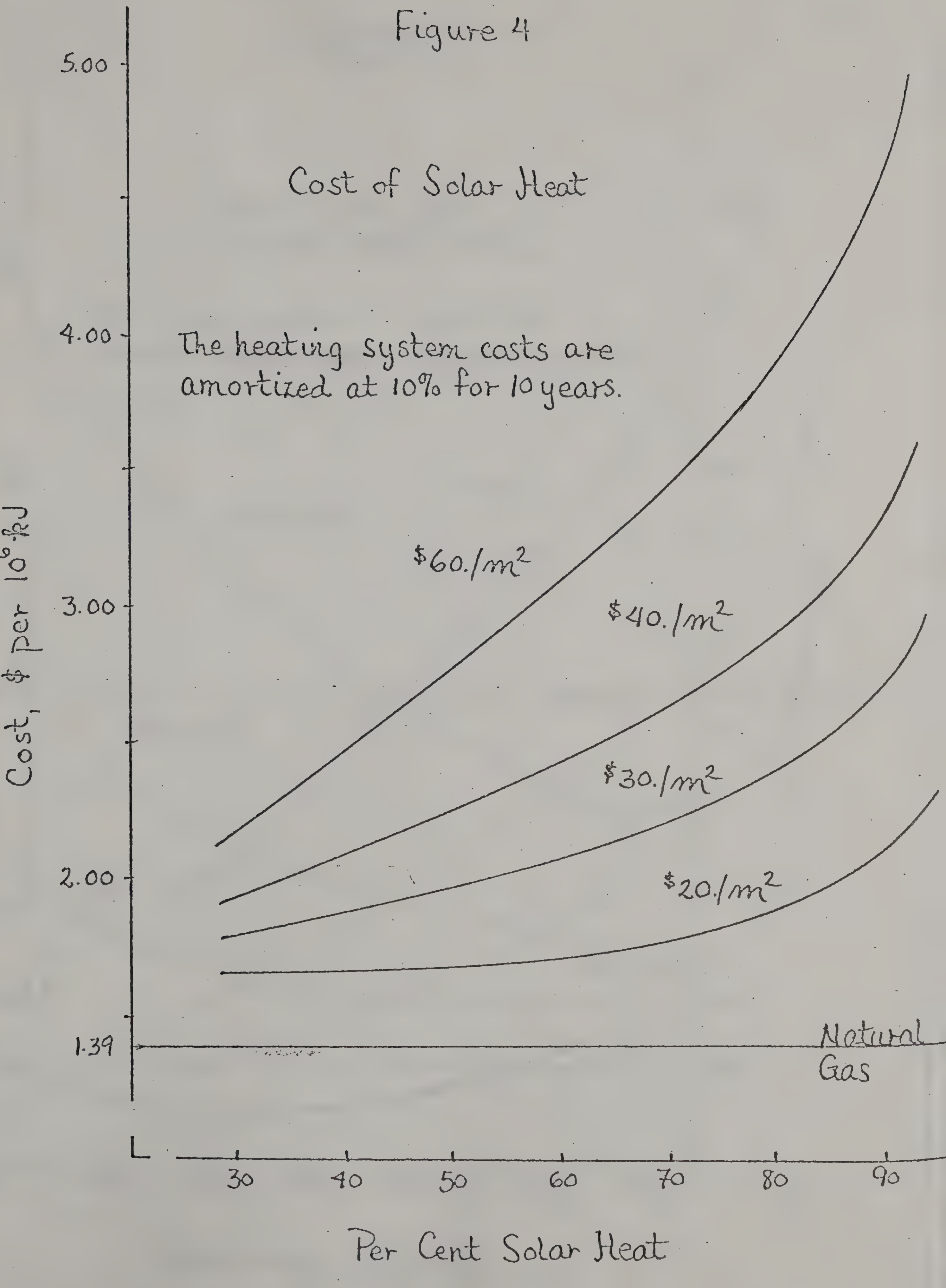

Cost of Solar Heat
The heating system costs are amortized at 10% for 10 years.
5.00
4.00
3.00
2.00
1.39
Cost, $ per 10⁶ kJ
$60./m²
$40./m²
$30./m²
$20./m²
Natural Gas
30
40
50
60
70
80
90
Per Cent Solar Heat

Figure 3

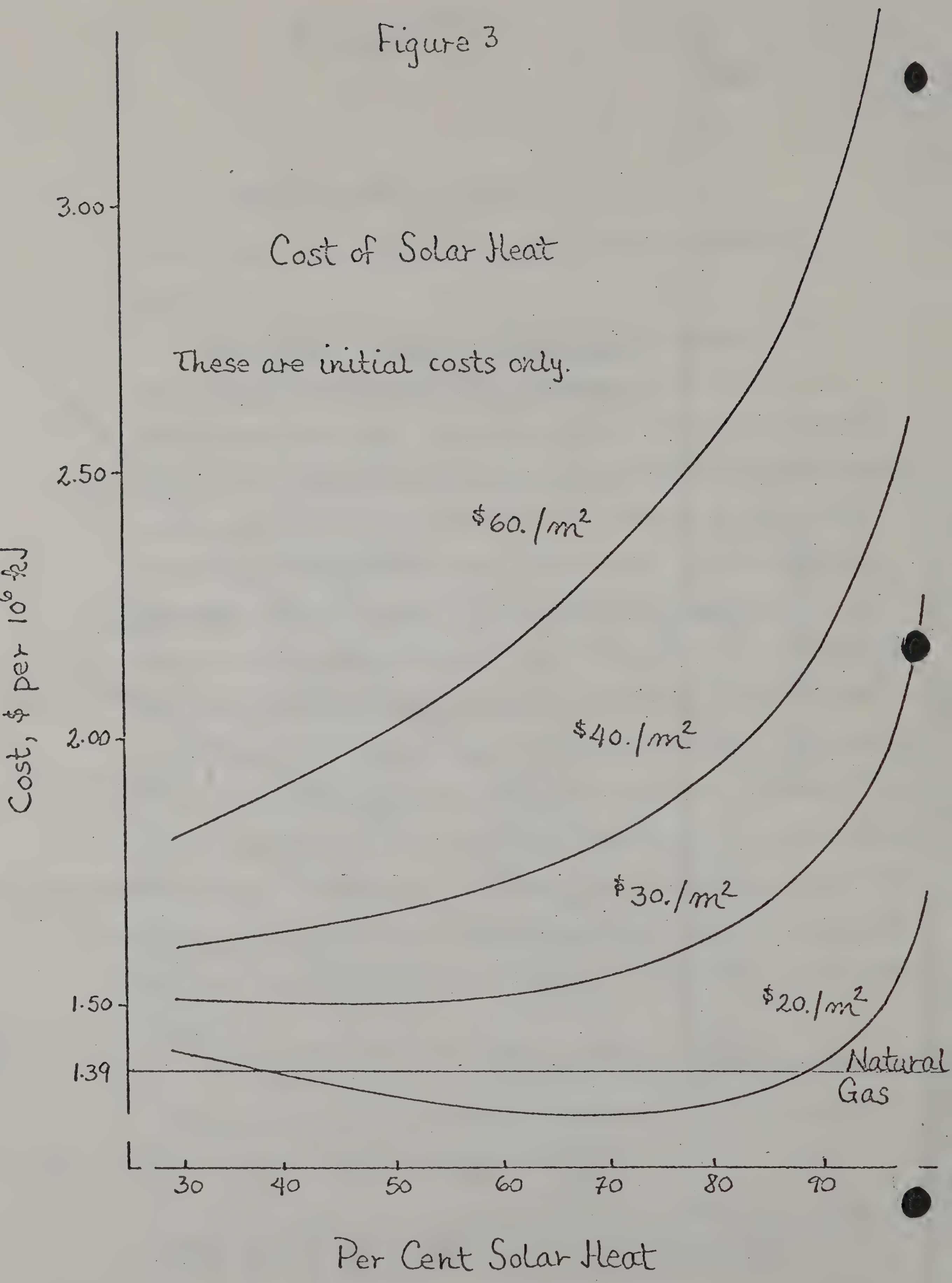
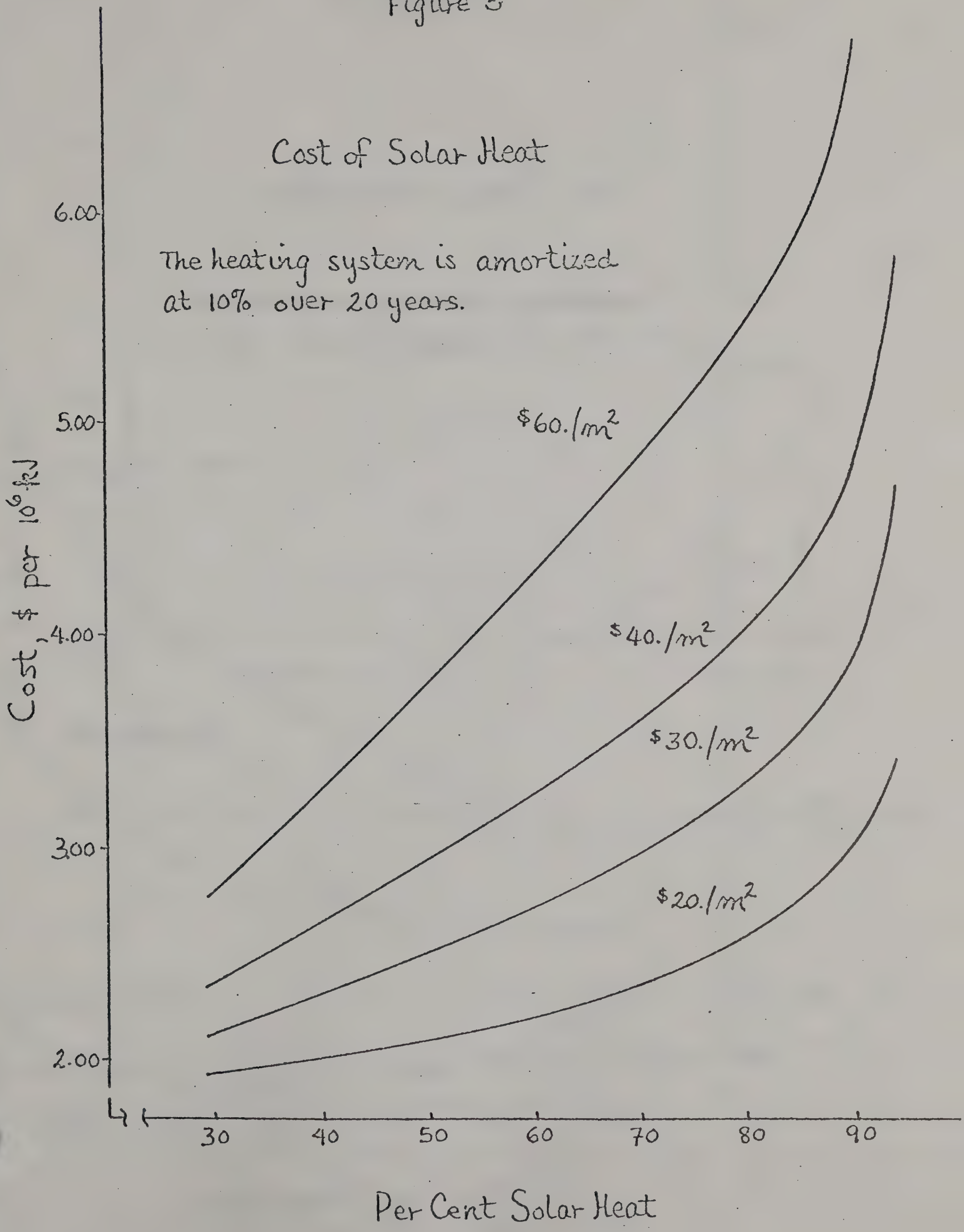

Cost of Solar Heat
These are initial costs only.
Cost, \$ per 10^6 kJ
3.00
2.50
2.00
1.50
1.39
\$60./m^2
\$40./m^2
\$30./m^2
\$20./m^2
Natural Gas
30
40
50
60
70
80
90
Per Cent Solar Heat

Figure 5



Cost of Solar Heat
The heating system is amortized at 10% over 20 years.
$60./m²
$40./m²
$30./m²
$20./m²
6.00
5.00
4.00
3.00
2.00
Cost, $ per 10⁶ kJ
30
40
50
60
70
80
90
Per Cent Solar Heat

Figure 6

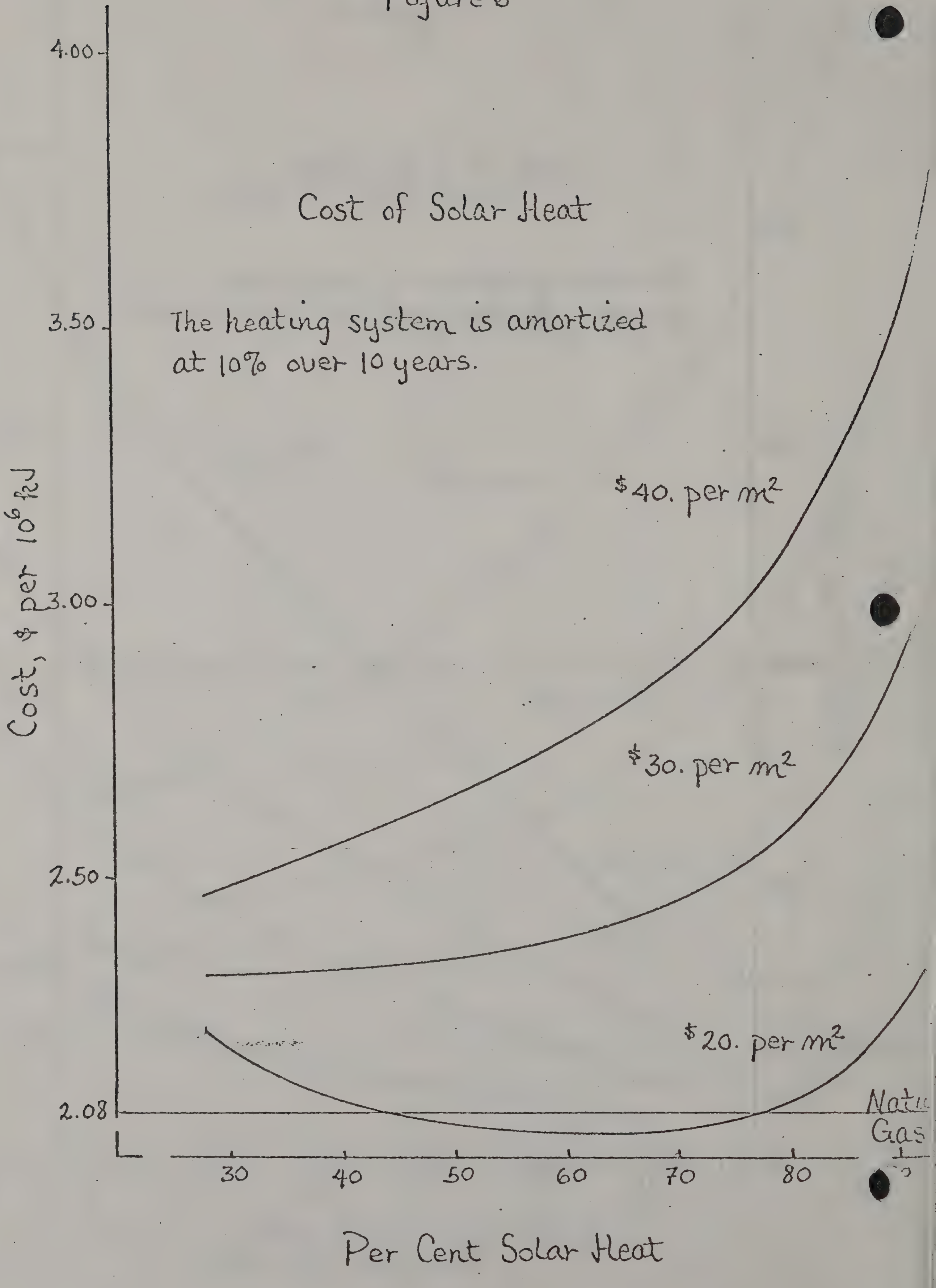

Cost of Solar Heat
The heating system is amortized at 10% over 10 years.
$40. per m²
$30. per m²
$20. per m²
Gas
4.00
3.50
3.00
2.50
2.08
30
40
50
60
70
80
Cost, ¢ per 10⁶ kJ
Per Cent Solar Heat

Figure 7

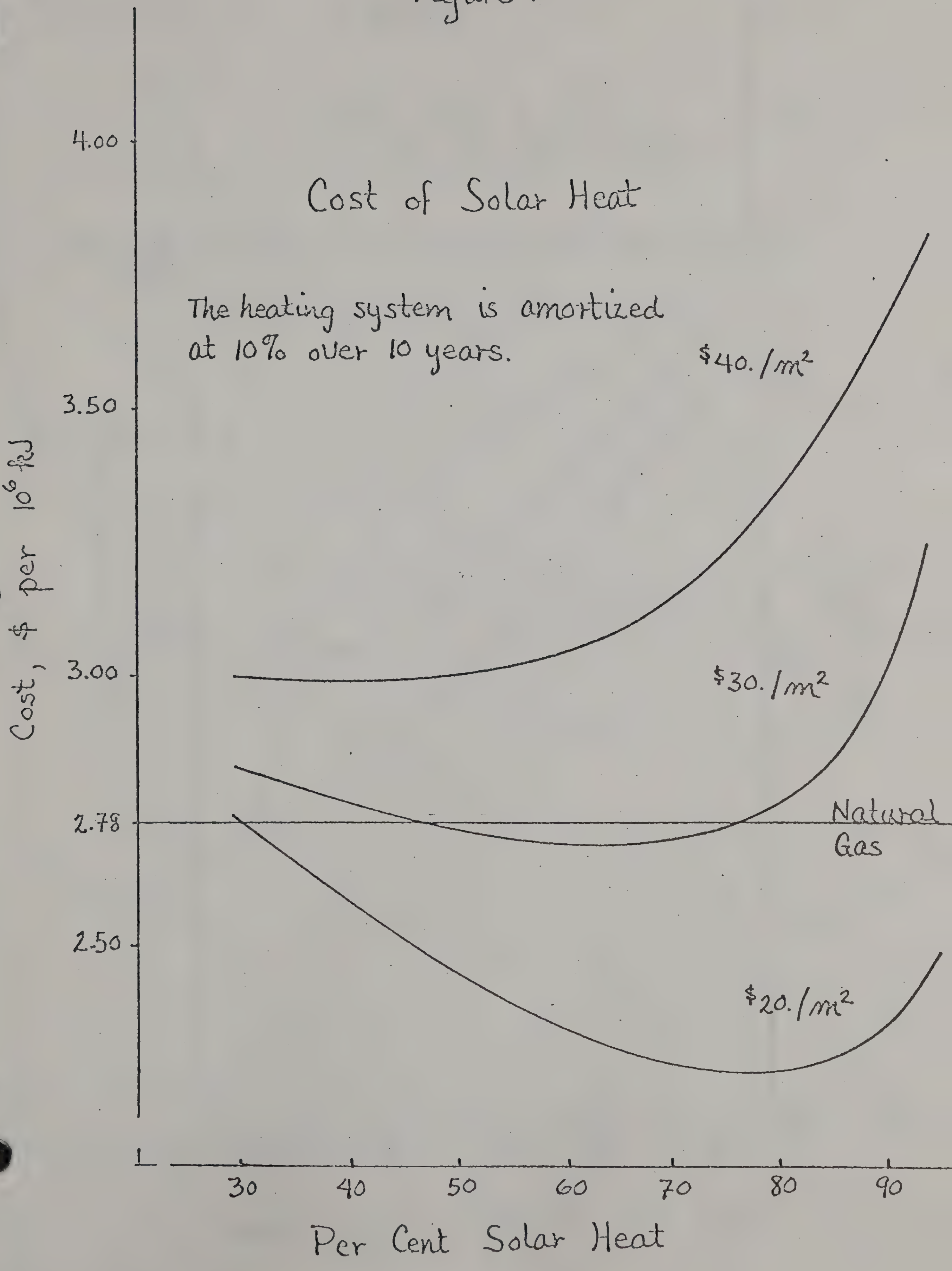
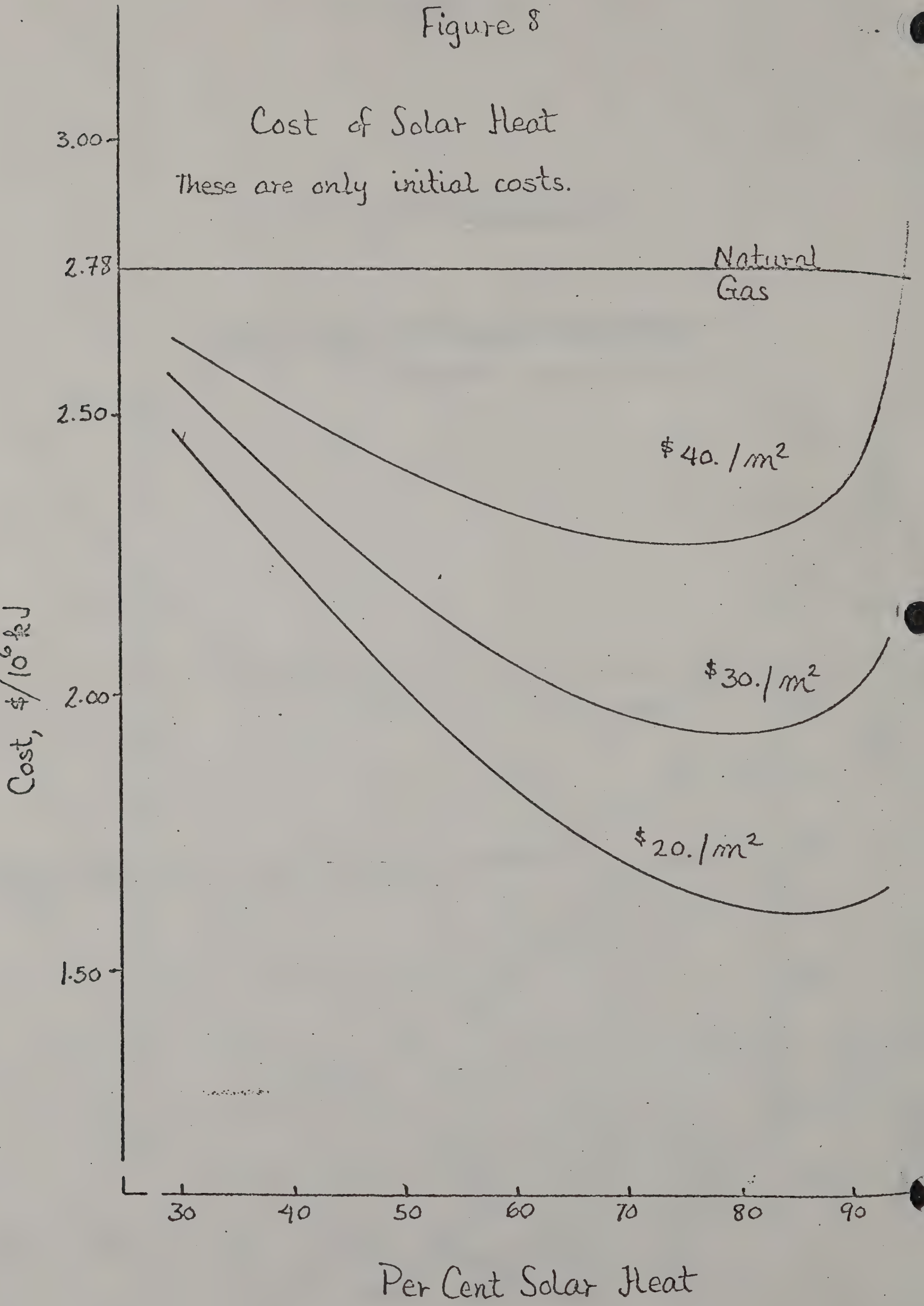

Cost of Solar Heat
The heating system is amortized at 10% over 10 years.
$40./m²
$30./m²
$20./m²
Natural Gas
4.00
3.50
3.00
2.78
2.50
Cost, $ per 10⁶ kJ
30
40
50
60
70
80
90
Per Cent Solar Heat

Figure 8



Cost of Solar Heat
These are only initial costs.
3.00
2.78
2.50
2.00
1.50
Natural Gas
$40./m²
$30./m²
$20./m²
Cost, $/10⁶ kJ
30
40
50
60
70
80
90
Per Cent Solar Heat

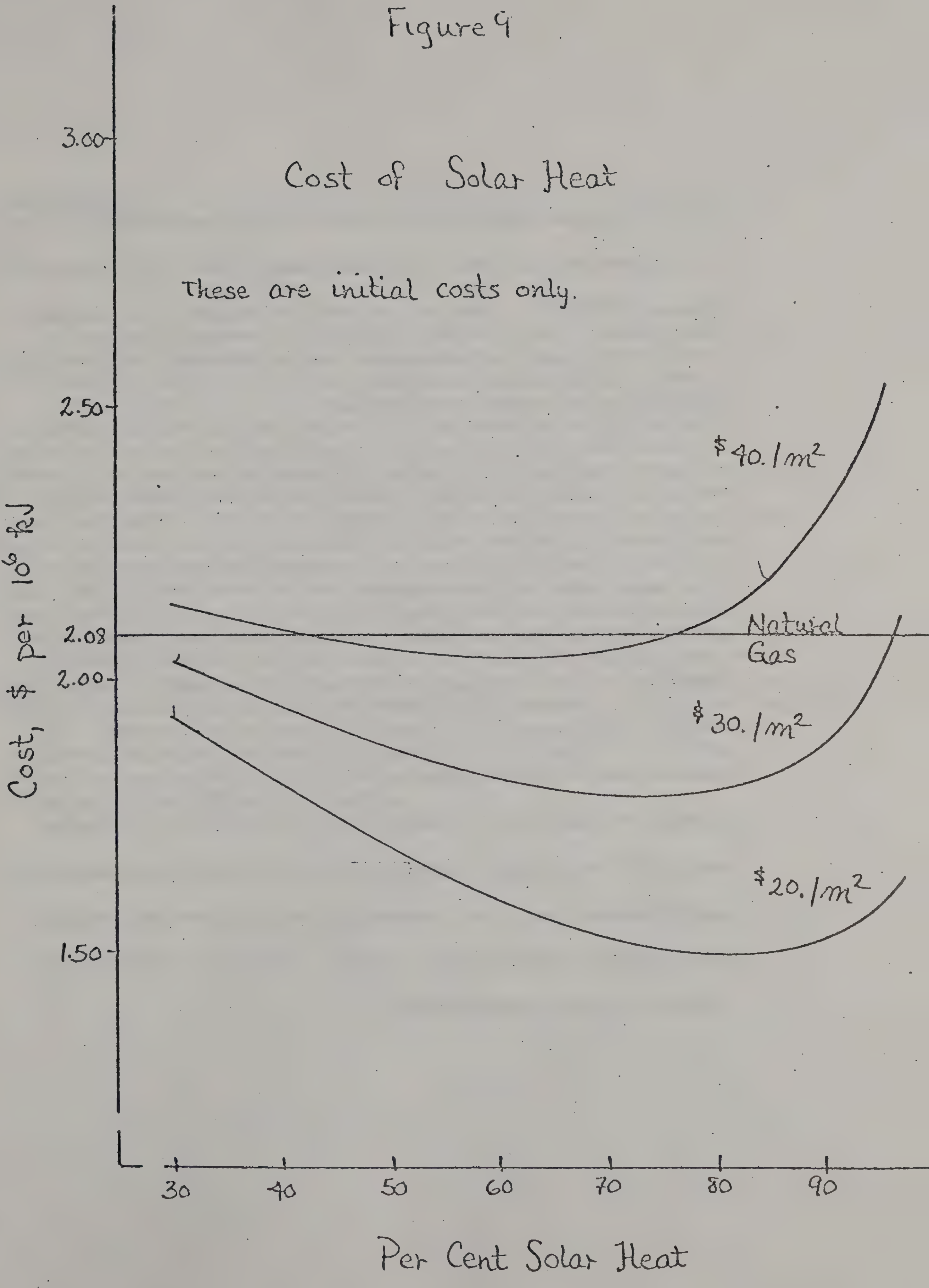


Figure 9
Cost of Solar Heat
These are initial costs only.
3.00
2.50
2.08
2.00
1.50
Cost, $ per 10^6 kJ
$40./m²
Natural Gas
$30./m²
$20./m²
30
40
50
60
70
80
90
Per Cent Solar Heat

see what happens when prices increase by 50% and 100%. The costs of solar-natural gas heat for these energy costs are displayed in figures 6,7,8 & 9 . Now we see that solar heat does certainly become economically advantageous even in Montana. In fact, quite large collector areas are justified.

What does this all mean? Simply that the future holds promise for solar heating systems and even the present bodes well for solar heat depending on the terms to which you and your banker can agree. If an absorption air conditioning system were added to the solar heating system, the collectors could operate year round, thus reducing the cost per unit of energy. The amount of reduction would be contingent on the cost of the air conditioner. If someone were to invest in a solar heating system now, he would probably be faced with several years of relatively expensive energy for heating and cooling (unless he would have otherwise used electric heat), but eventually he will have the economic advantage over conventional systems. Perhaps a solar heating system is worth consideration.

appendix 4

To find the power contained in the wind let's assume that it has a density ρ and a velocity v. The kinetic energy E of anything that is moving is $E = 1/2\ mv^2$ where m is its mass and v its velocity. Then if we have air of density ρ moving v meters/sec, ρv gives us the mass that moves through an area of 1 m^2 in one sec. So, since power P is the time rate of change of energy, $P = 1/2\ \rho v \cdot v^2 = 1/2\ \rho v^3$. Note that although I've treated ρ as a constant for the purpose of calculating power in tables 1 and 2, it is not a constant but varies with temperature, humidity and atmospheric pressure. A typical range of densities might be from 900 gm/m^3 to 1.3198 gm/m^3. I chose 1000 gm/m^3 for tables 1, 2, and 4.

appendix 5: conversion factors, etc.

to change	into	multiply by
m	cm	100
atmospheres	cm of mercury	76.0
BTU	cal	252
BTU	joules	1,055
BTU	kwhr	2.93×10^{-4}
BTU/ft^2	langleys	0.271
cal	BTU	3.97×10^{-3}
cal	joules	4.184
cal/min	watts	0.0698
cm	inches	0.394
cm^3	$inches^3$	0.0610
$inches^3$	cm^3	16.4
ft	m	.305
hp	kw	.745
inches	cm	2.54
joules	BTU	9.48×10^{-4}
joules	cal	0.239
Cal (kcal)	BTU	3.97
kg	lb	2.20

to change	into	multiply by
kw	hp	1.34
kwhr	BTU	3,413
langleys	BTU/ft^2	3.69
langleys/min	$watts/cm^2$	0.0098
m	ft	3.28
m	miles	6.21×10^4
lb	kg	.454
cm^2	$inches^2$	.155
cm^2	ft^2	1.08×10^{-3}
ft^2	m^2	.0929
ft^2	cm^2	929
m^2	ft^2	10.8
tons	kg	907
$watts/cm^2$	langleys/min	14.3
° Fahrenheit	° Centigrade	subtract 32 and multiply by .555 (or 5/9)
° Centigrade	° Fahrenheit	multiply by 1.8 (or 9/5) and add 32

Throughout the paper I've used the metric or SI system of units where convenient. For those not familiar with them, the table of conversion factors might help in getting an unfamiliar set of units into one more familiar.

An additional brief note: BTU, cal, Cal or kcal, joules, and kwhr (kilowatt-hours) are always units of <u>energy</u>. Power, which is the rate at which energy is expended or delivered (in other words energy divided by time), is always expressed in watts, kw or kilowatts (1000 watts), or hp (horsepower). One langley is defined as 1 cal per square centimeter (cal/cm^2). Also, I use ft^2, $inches^2$, $miles^2$, m^2, cm^2, m^3, and cm^3 to mean square feet, square inches, square miles, square meters, square centimeters, cubic meters and cubic centimeters, respectively. It is standard notation. Cal/cm^2 may alternatively be written cal/cm^{-2} and likewise $watts/cm^2$ may be written watts cm^{-2}, etc.

appendix 6: manufacturers and retailers of solar energy equipment

1.	W. R. Robbins & Son 1401 N. W. 20th St. Miami, FL 33101	solar water heaters
2.	FAFCO, Inc. (Freeman A. Ford) 2860 Spring St. Redwood City, CA 94063	swimming pool heaters
3.	Solar Energy Digest P.O. Box 17776 San Diego, CA 92117	importer of Beasley hot water heaters
4.	Sunworks, Inc. 669 Boston Post Road Builford, CT 06437	designers and builders of solar heating systems
5.	Tranter, Inc. 735 E. Hazel St. Lansing, MI 48924	"econocoil" solar water heater collector plates
6.	Energex Corp. 5441 Paradise Road Las Vegas, NV 89114	water heater collectors
7.	Solar Wind Co. East Holden, ME 04429	retailers of Quirks, Wincharger, and Elektro wind generators
8.	Fred Rice Productions, Inc. 6313 Peach Avenue Van Nuys, CA 91401	solar water heaters
9.	Olin Corporation East Alton, IL 62024	manufactures flat plates for solar collectors

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